National Aeronautics and Space Administration

Engine Icing Performance Simulation

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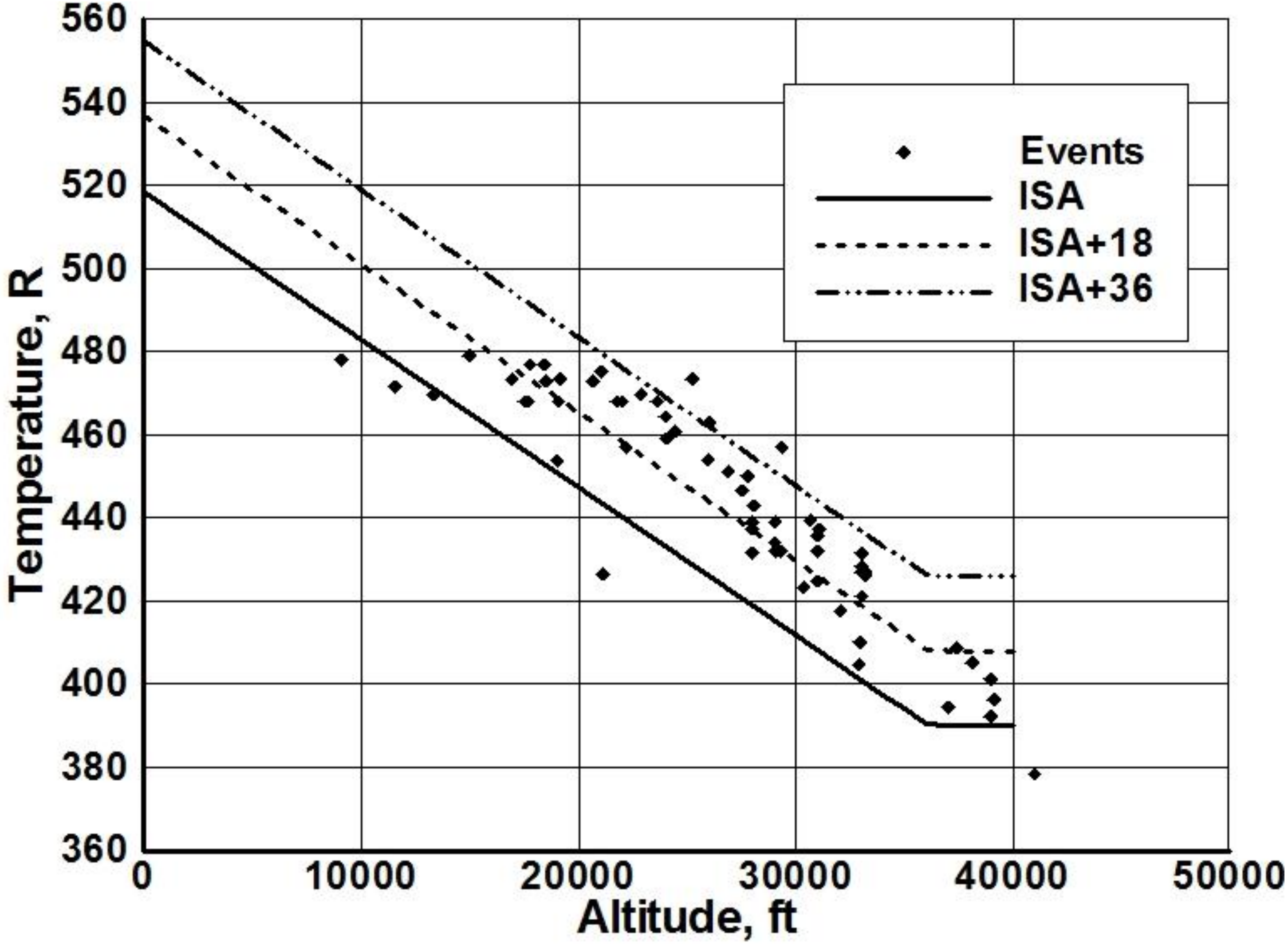
Outline

- Background
- Approach
- Results
- Summary and Conclusions

Background

- Commercial Airlines have reported ice accretion events that have resulted in degraded engine performance in the form of engine roll back, compressor surge and stall, and even flameout of the combustor.
- Ice crystals are ingested into the engine low pressure compression (LPC) system, the air temperature increases and a portion of the ice melts allowing the ice-water mixture to stick to the metal surfaces of the engine core.
- There is a lack of computational tools that can predict the occurrence of ice accretion and its effects on the LPC and the engine system performance at altitude conditions.

Reported Engine Icing Events with ISA and Elevated Temperatures (+18, +36)



Approach

- Leverage from existing computational tools to simulate engine and compressor aerothermodynamic performance:
- NPSS - Numerical Propulsion System Simulation advanced thermodynamic code written in an object-oriented language for system modeling of gas turbine engines. Provides component level analysis.
- COMDES - a design and analysis mean line compressor flow code that provides detailed flow conditions between blade rows, velocity triangles, and overall performance.
- Couple the NPSS and COMDES codes such that they run concurrently, exchanging BCs at each operating point.
- NPSS-COMDES will produce the flow field through the fan-core and LPC along the flight trajectory. The flow field will be provided as BCs for subsequent analysis for ice accretion using GlennICE.

Approach (Continued)

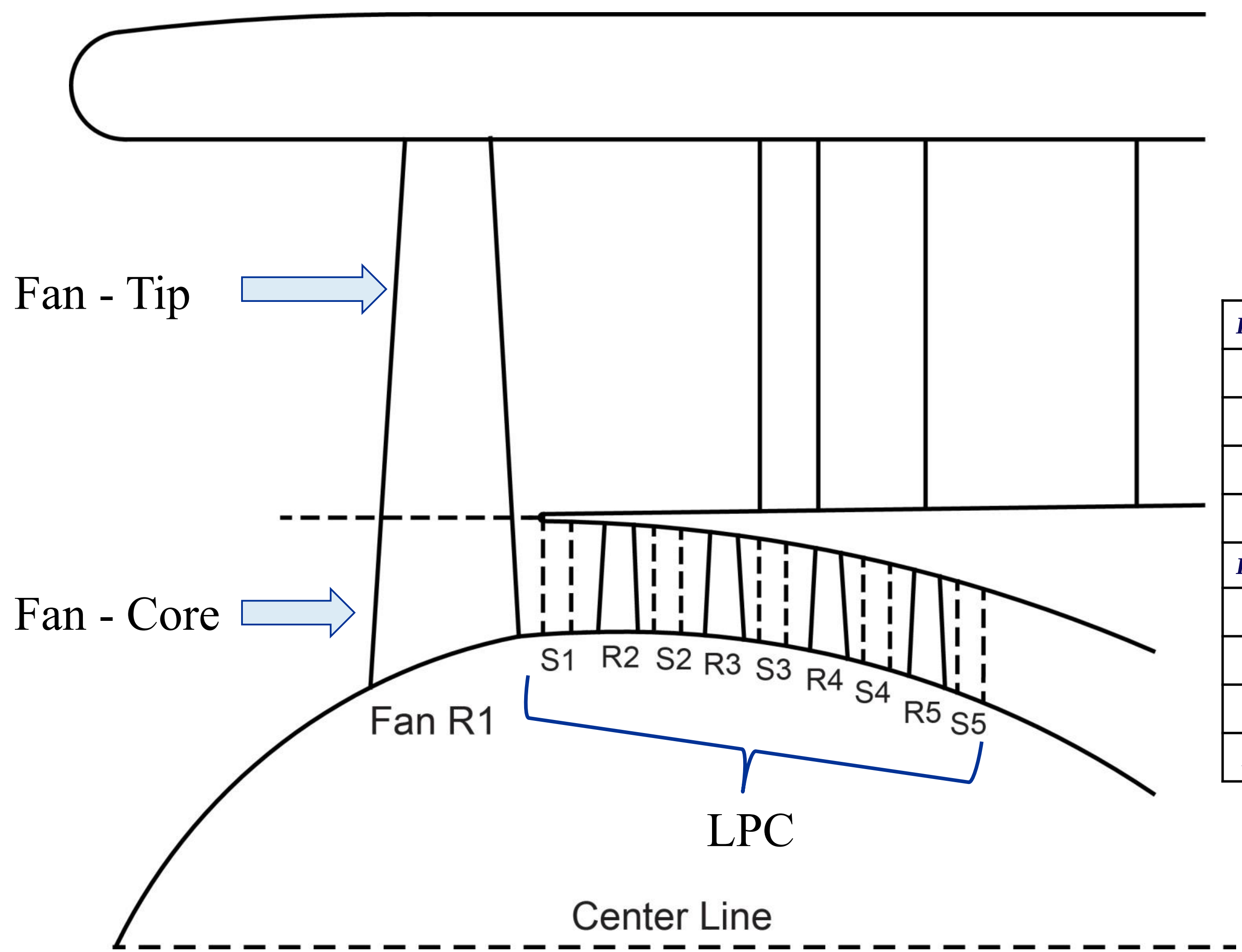
- Run the engine system code and the compressor analysis code concurrently such that blade-row to blade-row flow conditions can be computed along the flight trajectory.
  - Compute a baseline solution over a notional flight trajectory
  - Determine potential locations within the LPC where local flow conditions are favorable for ice accretion, initially based on static temperature.
  - Perform a parametric sensitivity analysis of ice blockage over the complete flight trajectory with the mean-line compressor analysis code coupled to NPSS, increasing the blockage within certain blade rows.
  - Analyze the fan-LPC in the engine systems environment. The analysis code coupled with NPSS effectively replaces the component (LPC) performance maps.

Approach (Continued)

- Lack of publicly available, non-proprietary engine geometry and performance data, necessitated a notional 40K lbf thrust class engine to be utilized for this study.
  - Conceptual design of fan and LPC was performed, since details were needed for the COMDES mean line flow analysis.
  - Produce a baseline performance map and superimpose the selected engine operating points through the flight trajectory, including cruise and descent.
- A temperature range where ice could accrete was initially assumed to be within a static temperature range of 509-515R, based on data in the literature.
- Currently NPSS and compressor flow analysis codes assume no humidity or ice / water in the flow.
- Parametric study of blockage in LPC stators currently assumes constant max thrust at each operating point.

Fan-Core and LPC Cross Section of 40K Thrust Class

Based on Conceptual Design with COMDES



Fan and LPC Design Point Objectives at Sea Level Takeoff

Fan – Tip	
Flow, lbm/sec	**1122**
Pressure Ratio	**1.701**
Efficiency	**91.1**
Shaft Speed, RPM	**3761.1**
Fan - Core & LPC	
Flow, lbm/sec	**172**
Pressure Ratio	**2.23**
Efficiency	**87.0**
Engine Bypass Ratio	***5.8***

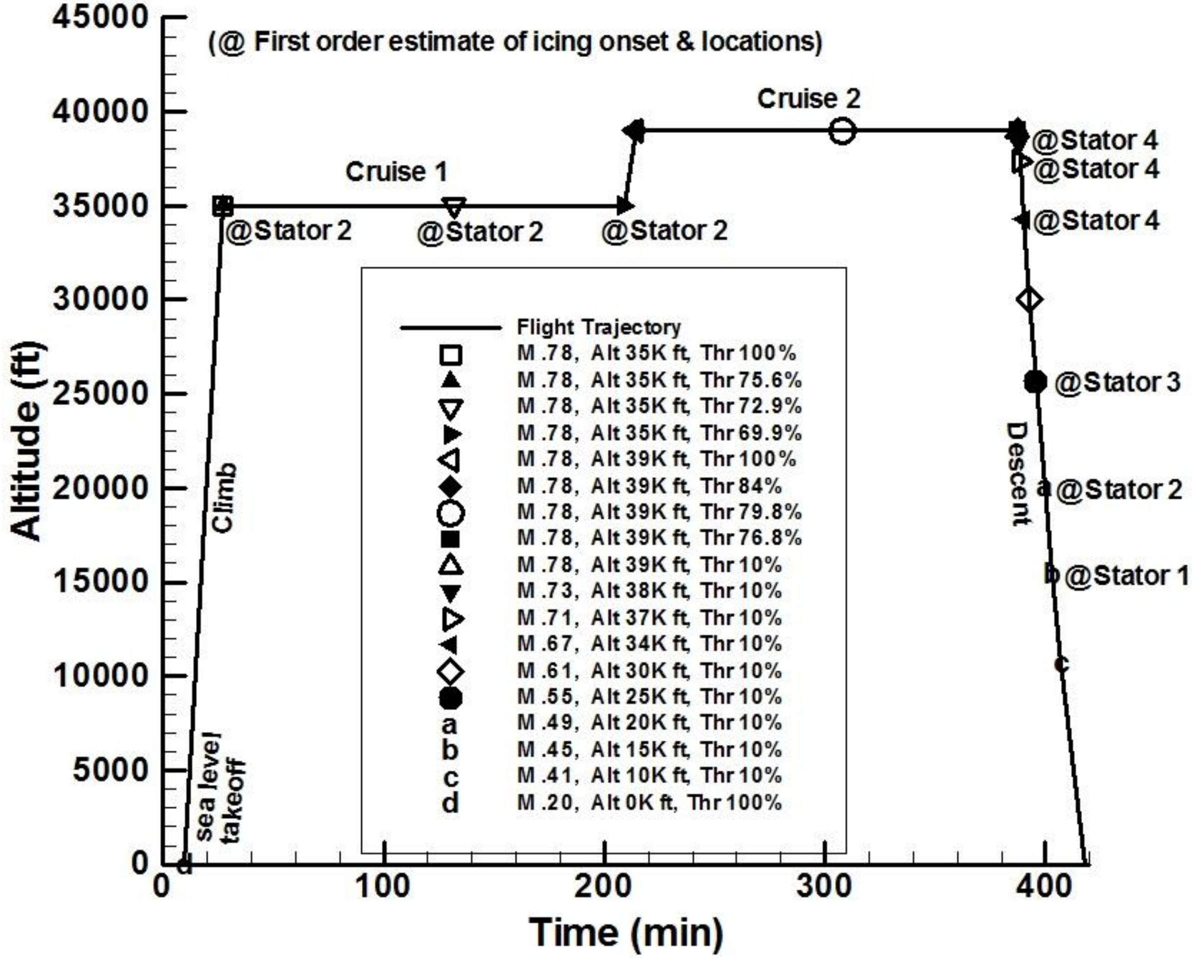
Fan-Core and LPC Design Point Geometric and Aerodynamic Parameters

	Fan-Hub Rotor1	Fan-Hub Stator1	LPC Rotor 2	LPC Stator 2	LPC Rotor3	LPC Stator 3	LPC Rotor 4	LPC Stator 4	LPC Rotor 5	LPC Stator 5
Leading Edge										
Press Stat., psia	**13.67**	**14.67**	**16.61**	**18.785**	**20.12**	**22.45**	**23.91**	**26.41**	**27.88**	**30.04**
Temp Static, R	**508.0**	**522.1**	**542.22**	**564.55**	**576.56**	**597.76**	**609.40**	**629.48**	**640.0**	**656.21**
Mach no., abs	**0.38**	**0.638**	**0.46**	**0.534**	**0.42**	**0.499**	**0.39**	**0.449**	**0.34**	**0.417**
Blade Angle	**47.20**	**35.4**	**42.3**	**30.6**	**23.5**	**31.5**	**43.80**	**32.4**	**44.80**	**33.0**
Abs Flow Angle	**0**	**36.15**	**0**	**31.22**	**0**	**32.18**	**0**	**33.00**	**0**	**0**
Tip Radius, in.	**20.63**	**20.6171**	**20.5304**	**20.3433**	**20.0960**	**19.6905**	**19.3131**	**18.8420**	**18.2524**	**17.6890**
Hub Radius, in.	**12.51**	**15.1021**	**15.2113**	**15.2026**	**15.0546**	**14.8484**	**14.3197**	**13.7204**	**13.0749**	**12.2606**
Trailing Edge										
Press Stat., psia	**14.69**	**16.35**	**18.76**	**19.79**	**22.40**	**23.56**	**26.19**	**27.53**	**30.06**	**31.22**
Temp Static, R	**521.86**	**539.72**	**563.96**	**573.81**	**597.00**	**606.82**	**627.60**	**637.69**	**655.84**	**663.90**
Mach no, abs.	**0.63**	**0.481**	**0.53**	**0.448**	**0.49**	**0.413**	**0.46**	**0.368**	**0.41**	**0.338**
Blade Angle	**12.7**	**0**	**23.5**	**0**	**23.5**	**0**	**23.5**	**0**	**23.5**	**0**
Abs Flow Angle	**36.93**	**0**	**31.59**	**0**	**32.30**	**0**	**32.27**	**0**	**33.24**	**0**
Tip Radius, in.	**20.63**	**20.5733**	**20.4459**	**20.1704**	**19.9256**	**19.4117**	**19.0737**	**18.4850**	**17.9280**	**17.2148**
Hub Radius, in.	**15.0**	**15.1901**	**15.2230**	**15.2026**	**14.8484**	**14.4742**	**13.9111**	**13.2848**	**12.4811**	**11.6228**

Sea level takeoff conditions

Notional Flight Trajectory

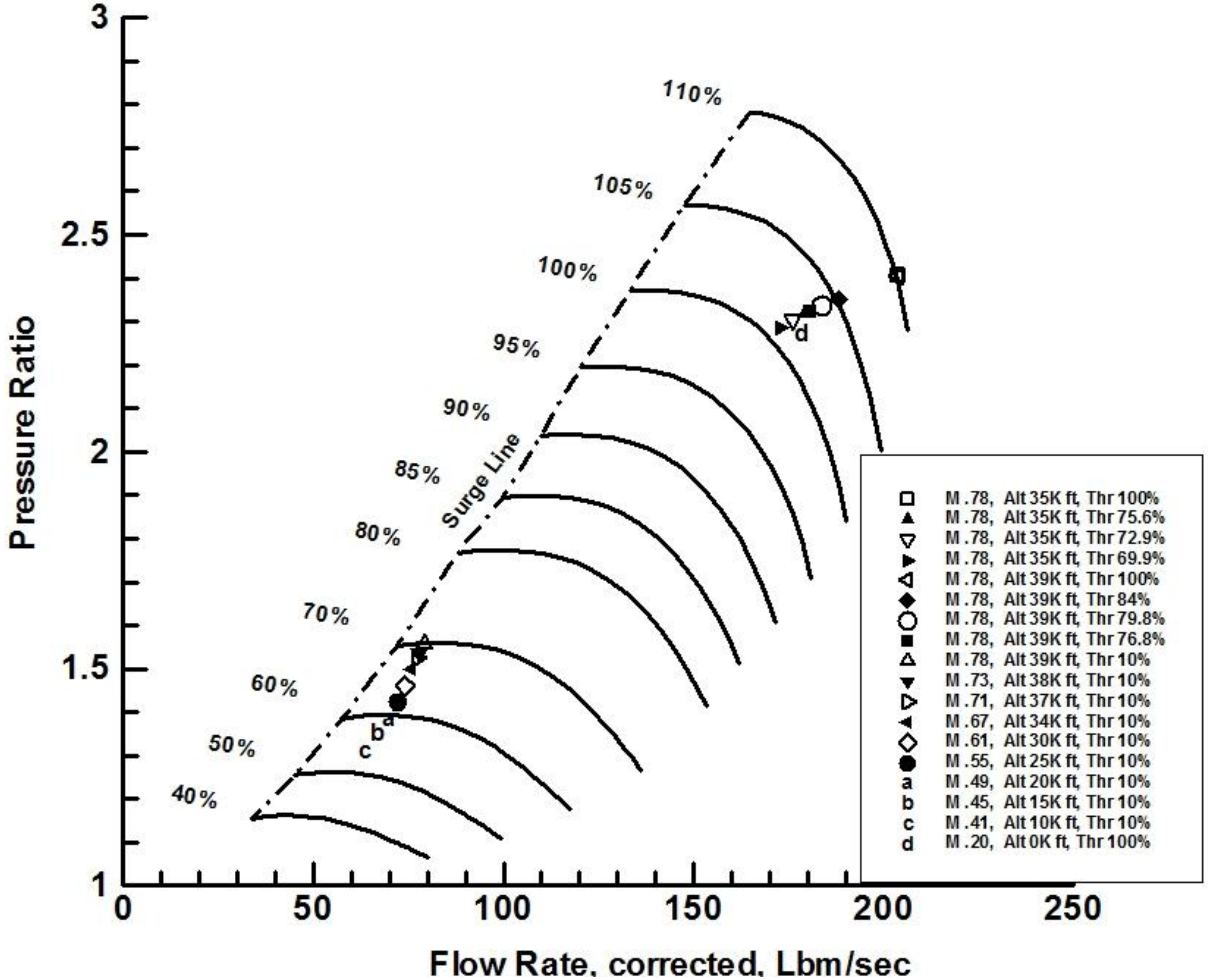
Ice Accretion Estimation Based on the NPSS – COMDES Analyses



Assumptions:

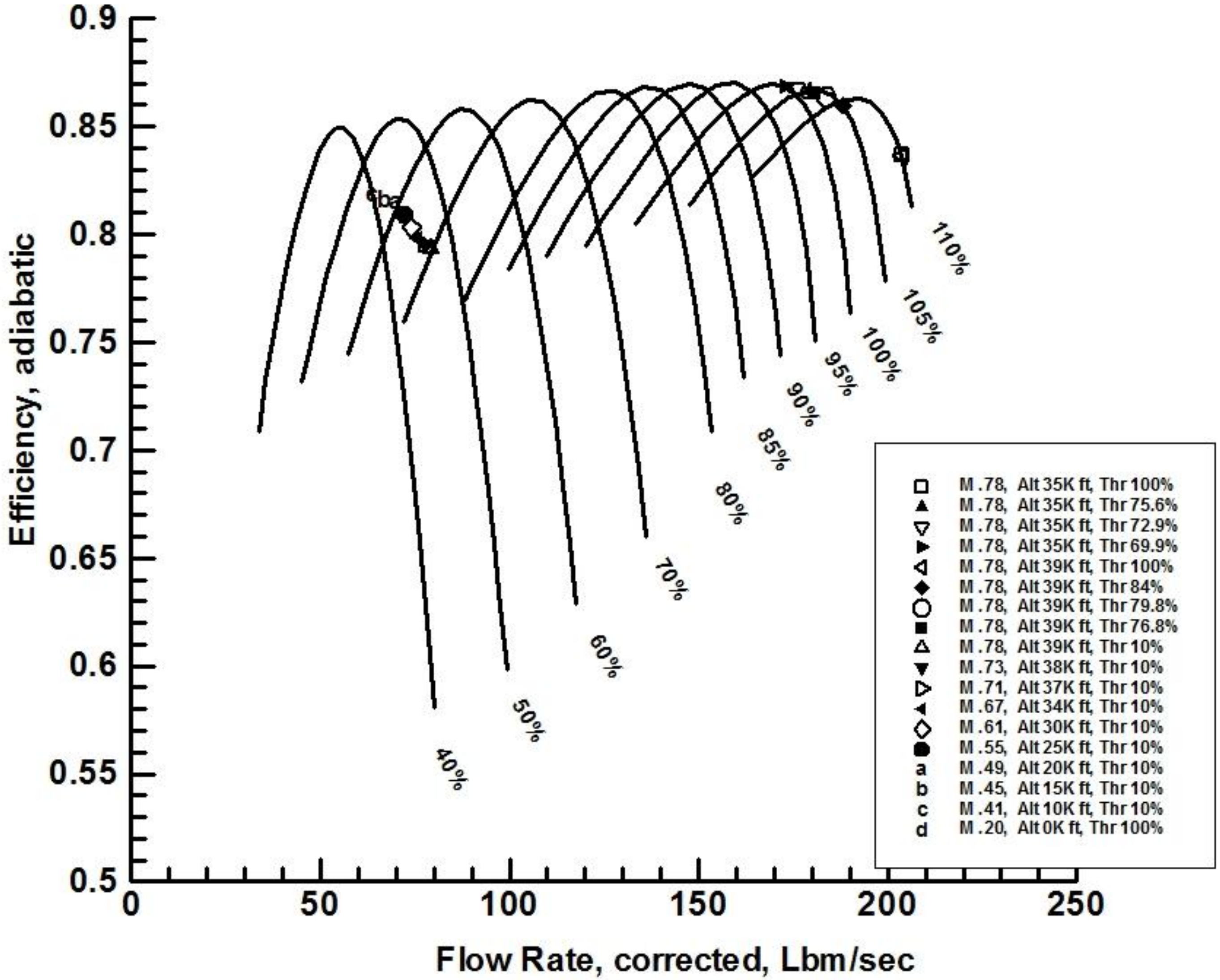
- Assumed temperature range where accretion occurs: 509-515 R
- Icing occurs in the fixed components only (stators).

Baseline Fan-Core and LPC Pressure Ratio Performance Map

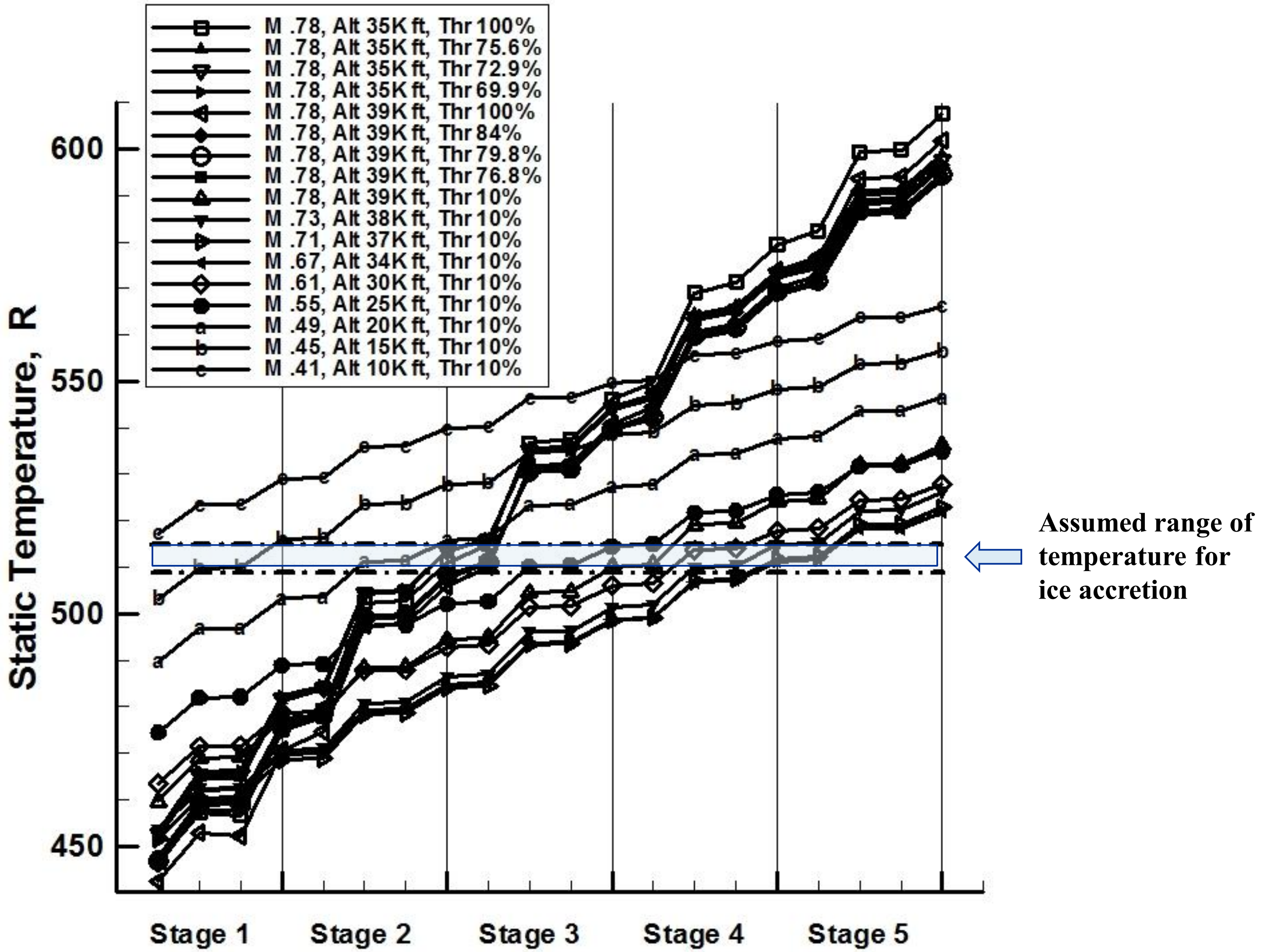


Operating points over the flight trajectory plotted on baseline performance map

Baseline Fan-Core and LPC Efficiency Performance Map



Static Temperatures in LPC through Engine Flight Trajectory



Tools for Estimating Engine and Detailed LPC Performance Through Vehicle Flight Trajectory

NPSS Model of Engine
Engine system performance to establish compressor BC's at altitude operating conditions through trajectory

Shaft Rotational Speed
Inlet Pressure
Inlet Temperature

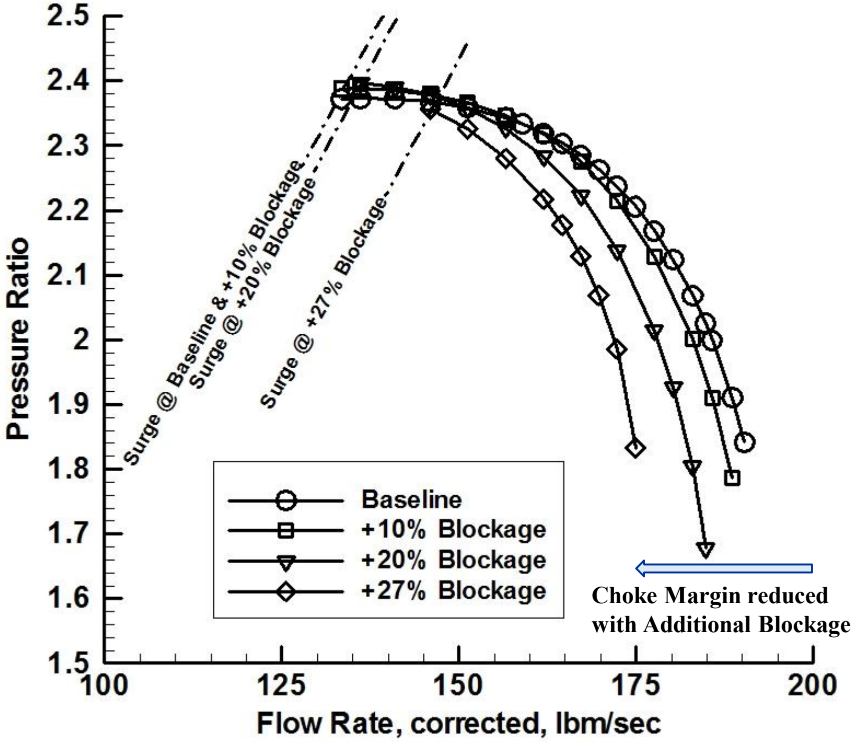
Pressure ratio, overall
Efficiency, overall

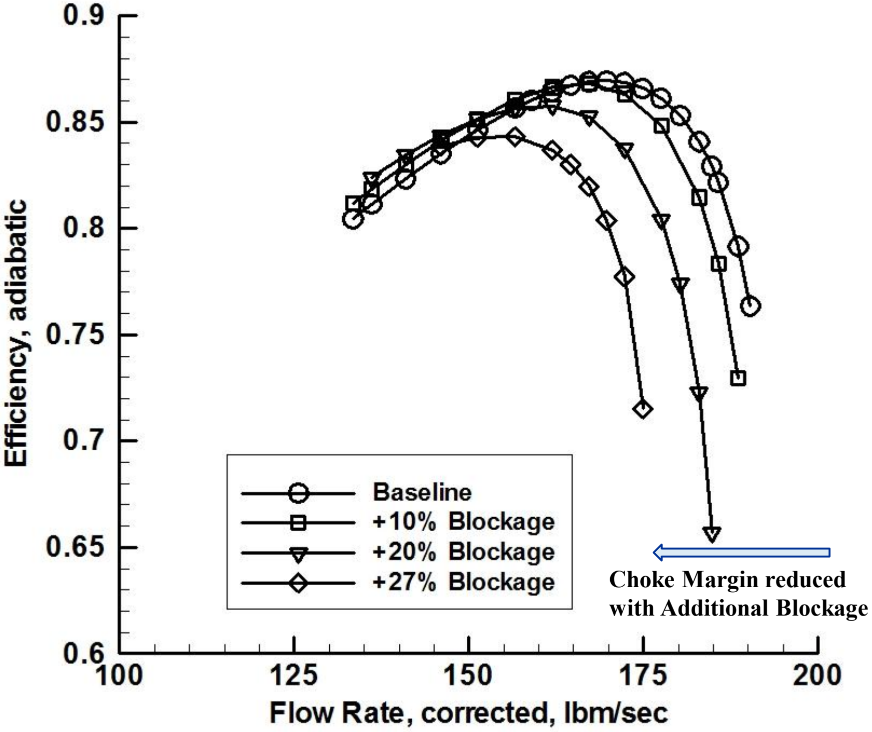
Compressor Flow Analysis
Flow analysis of the Fan core & LPC to determine blade row by blade row performance through the trajectory
(1D: COMDES, 2D: HT0300)

Flow field: blade-row by blade-row fluid conditions: static and total pressure, temperature, velocity triangles

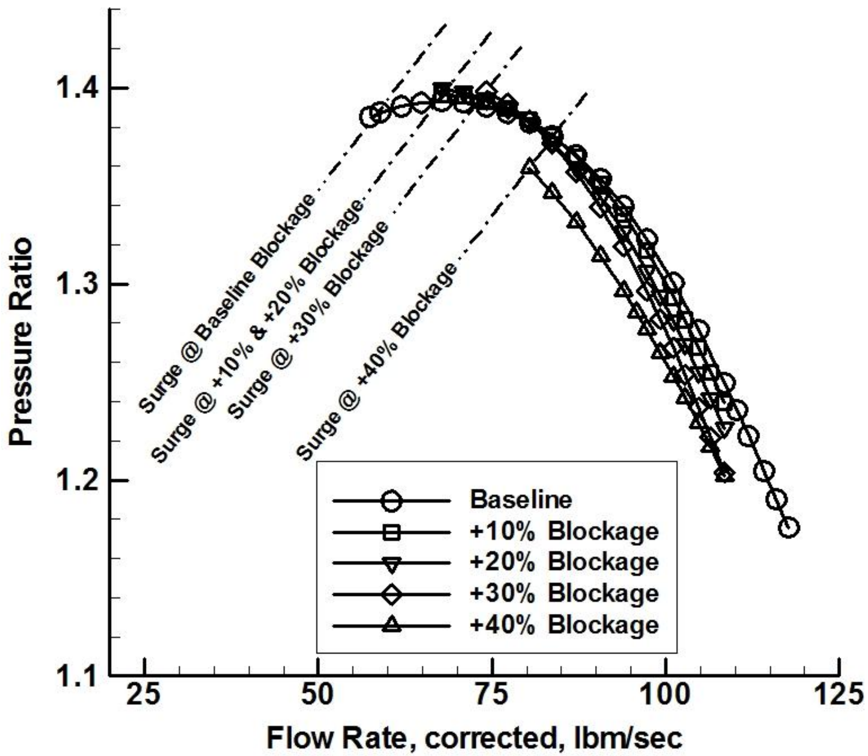
Ice Accretion Model
Estimate of the onset of icing location and rate of ice accretion in the fan & LPC along the flight trajectory
(2D: GlennICE, 3D: LEWICE3D)

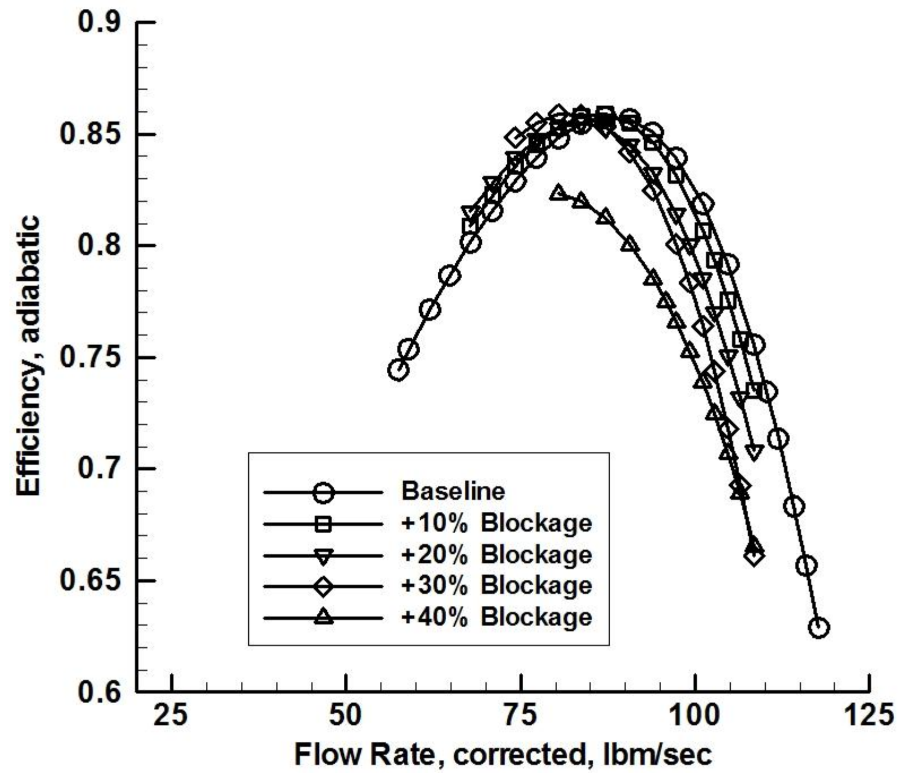
Overall Pressure Ratio and Efficiency at 100% Speed Line vs. Additional Blockage in Stage 2 Stator of LPC



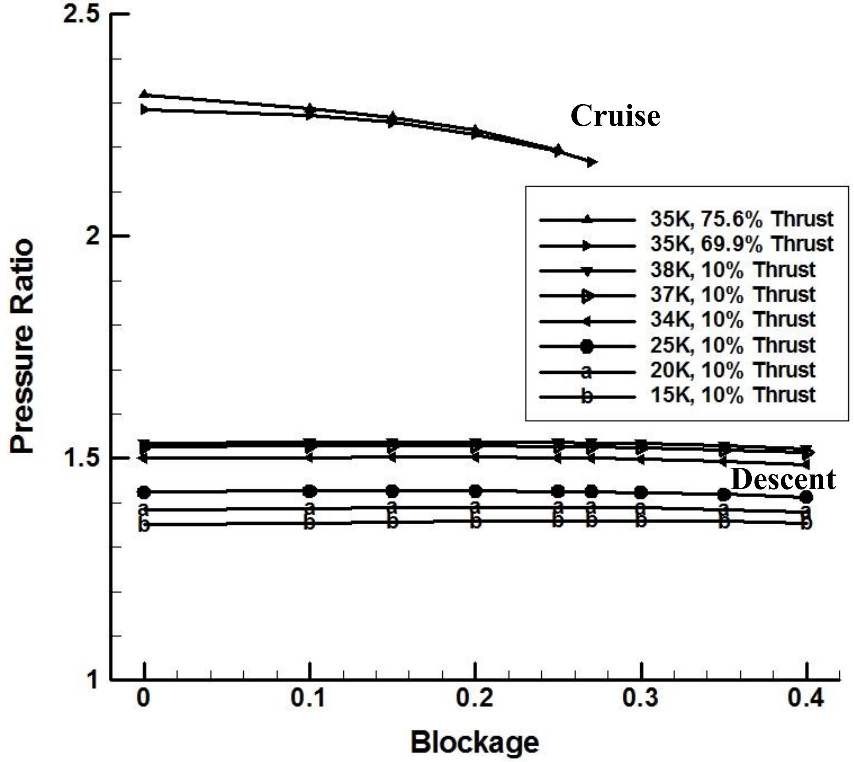


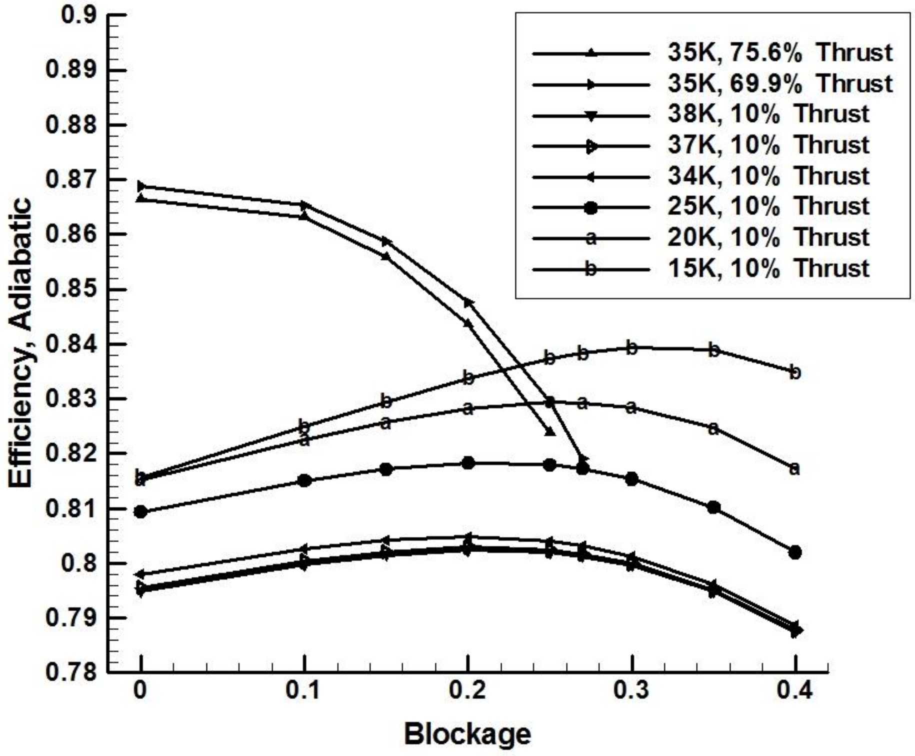
Overall Pressure Ratio and Efficiency at 60% Speed Line vs. Additional Blockage in Stage 2 Stator of LPC



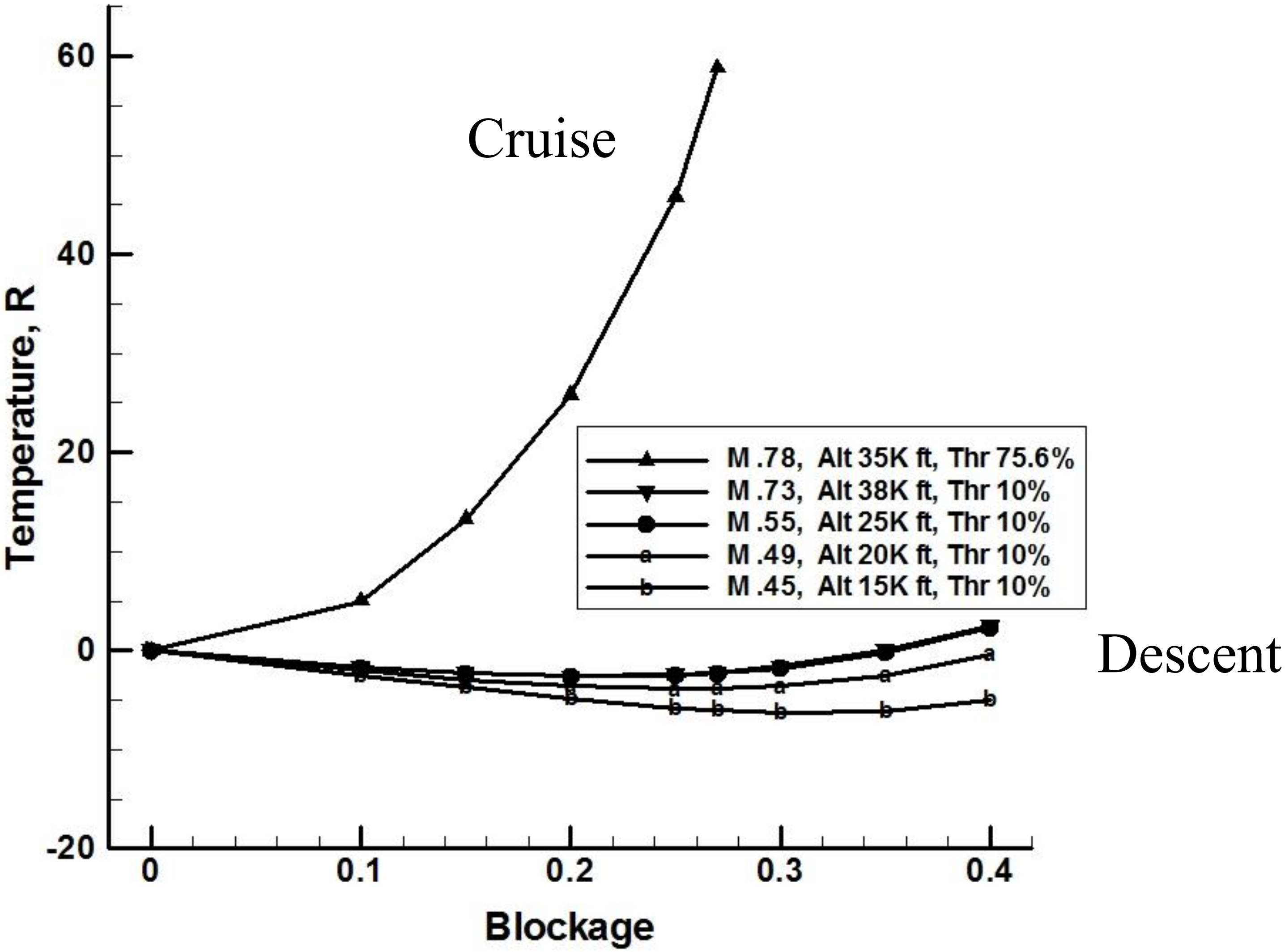


Effects of Additional Blockage on Overall Fan-Core and LPC Pressure Ratio and Efficiency along Flight Trajectory



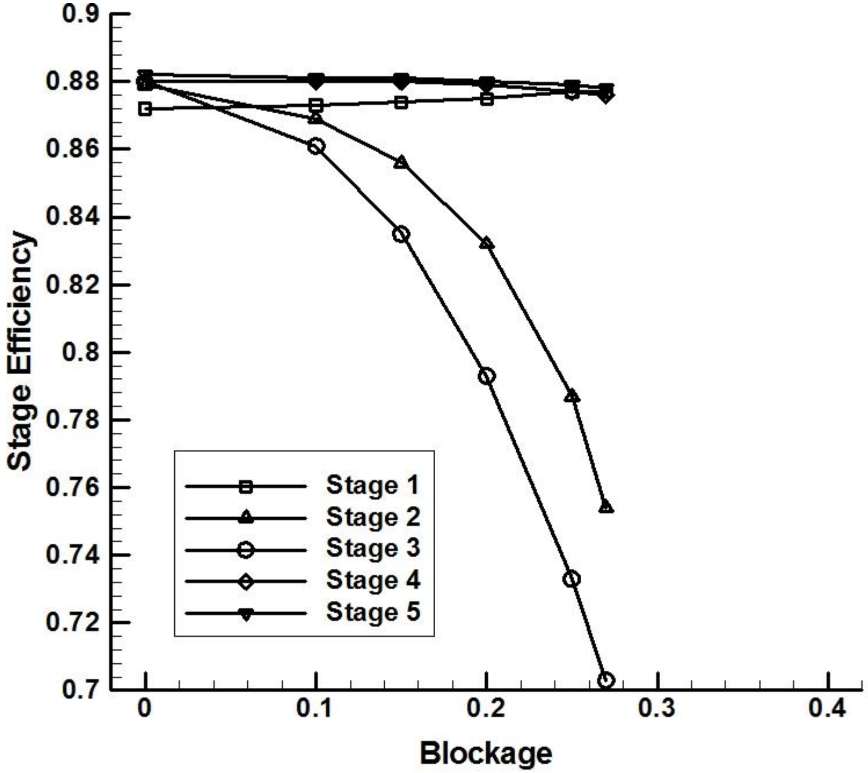


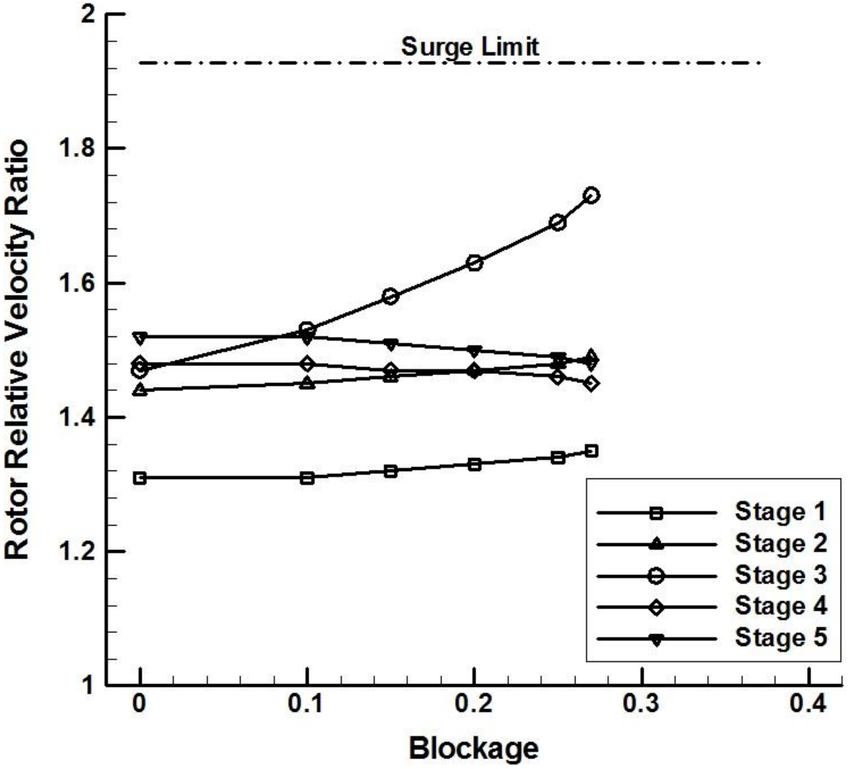
Effect of Additional Blockage in LPC on Turbine Inlet Temperature; from Baseline



Effect of Additional Blockage on Stage Efficiency and Rotor Relative Velocity Ratio, Blockage in Stage 2

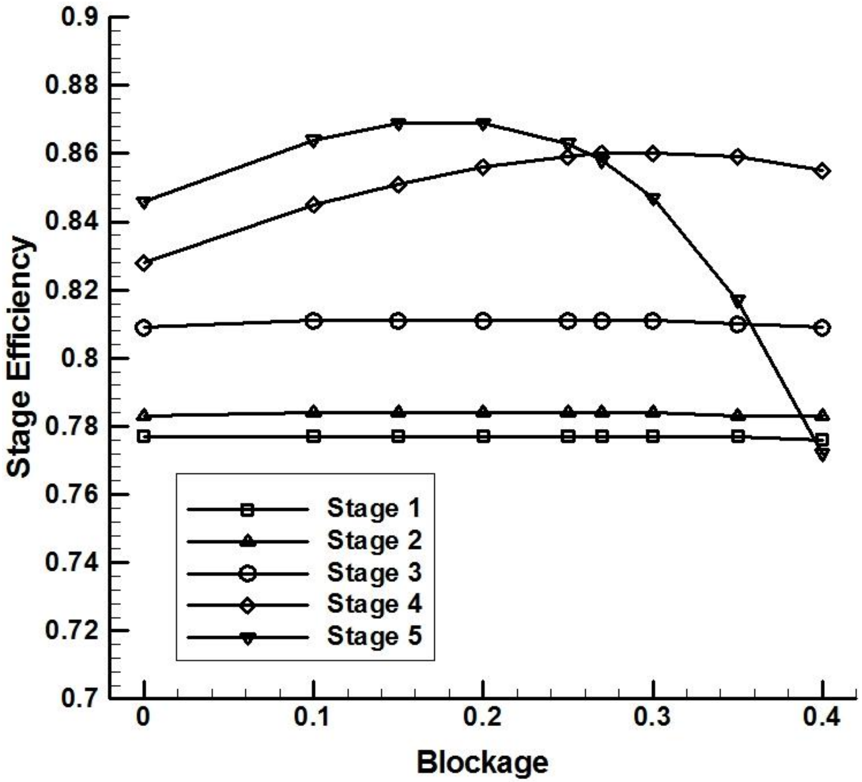
Inlet Mach .78, Altitude 35K ft, Thrust 75.6%

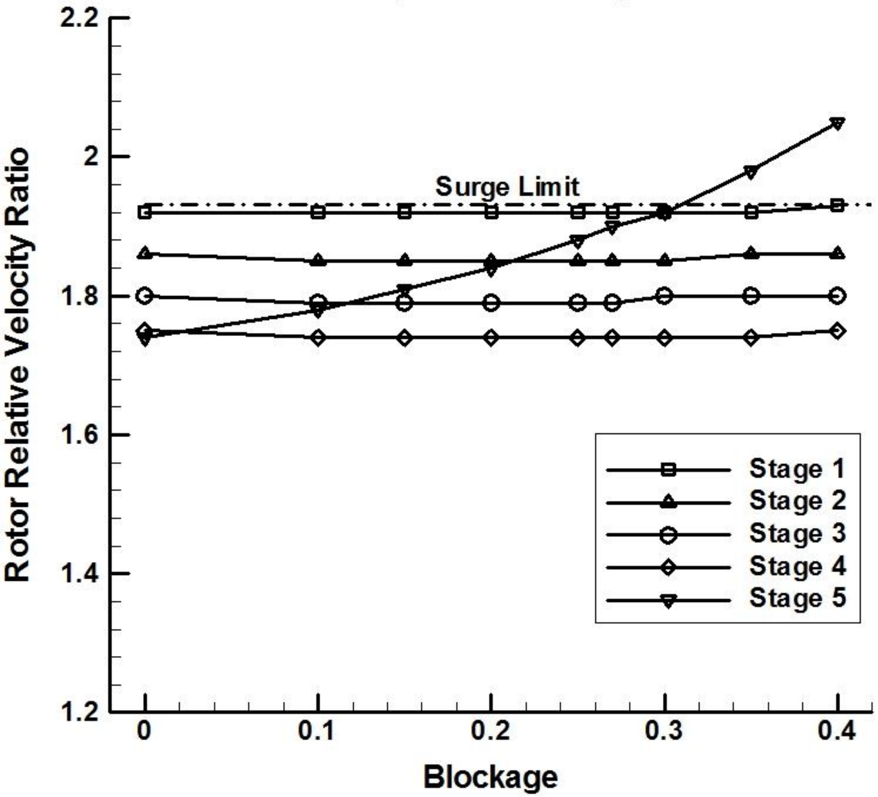




Effect of Additional Blockage on Stage Efficiency and Rotor Relative Velocity Ratio, Blockage in Stage 4

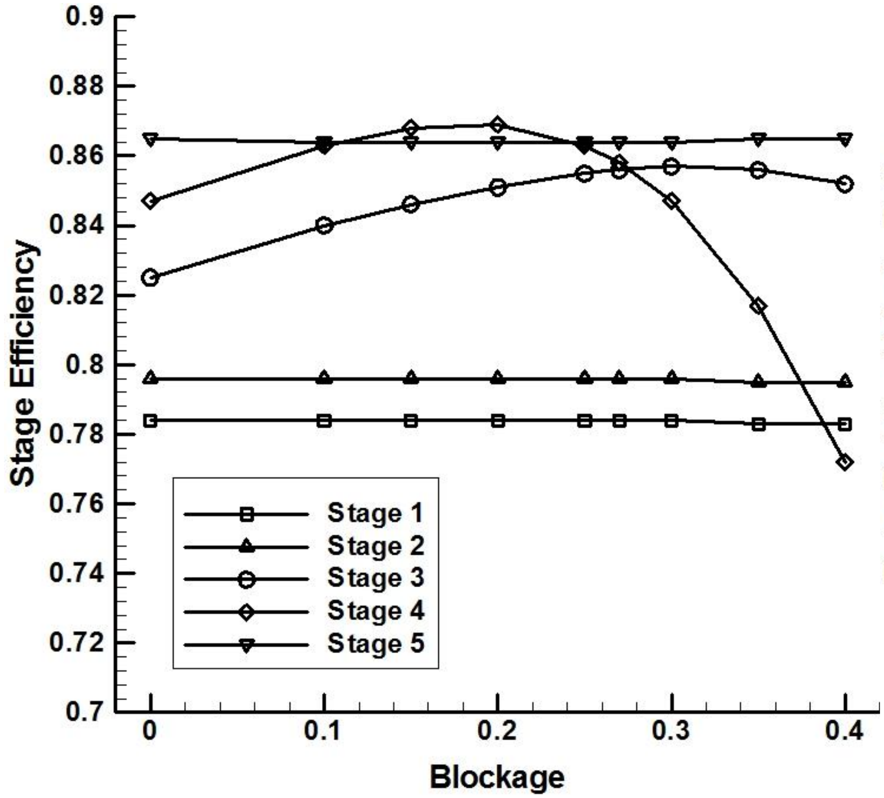
Inlet Mach .73, Altitude 38K ft, Thrust 10%

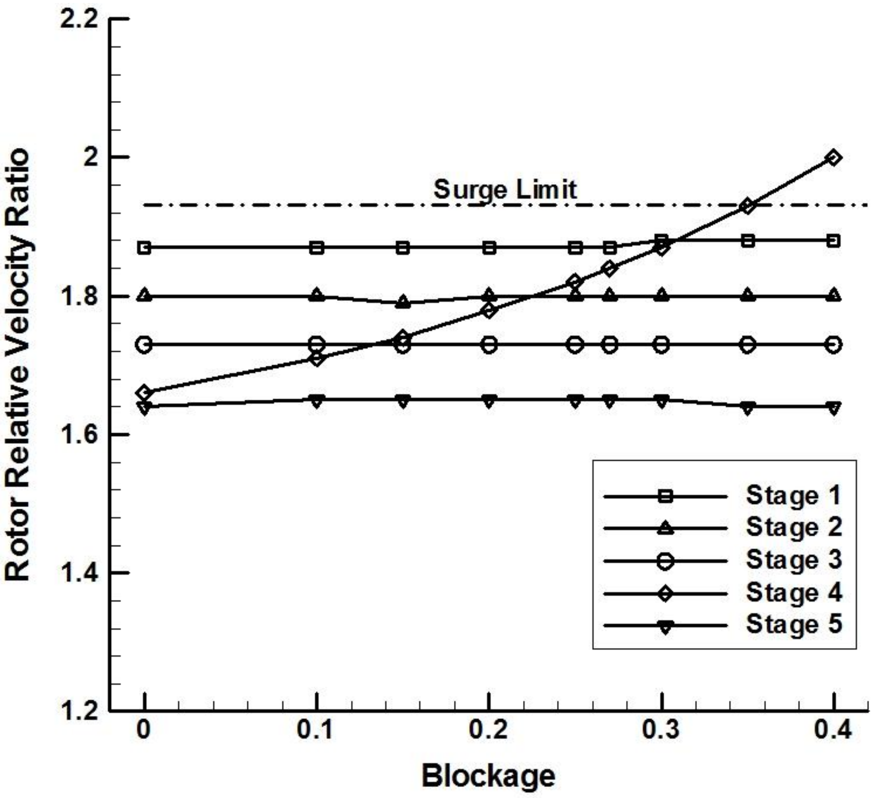




Effect of Additional Blockage on Stage Efficiency and Rotor Relative Velocity Ratio, Blockage in Stage 3

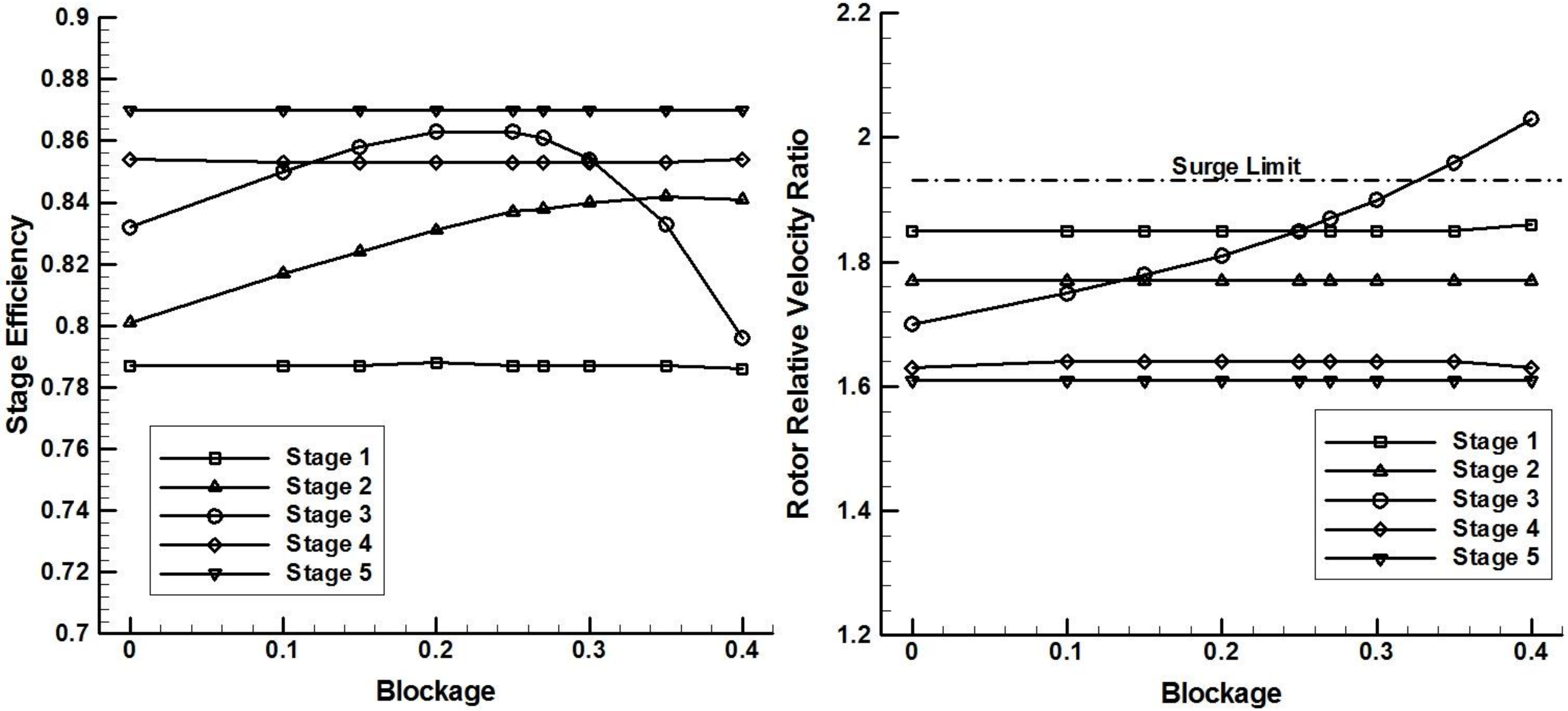
Inlet Mach .55, Altitude 25K ft, Thrust 10%





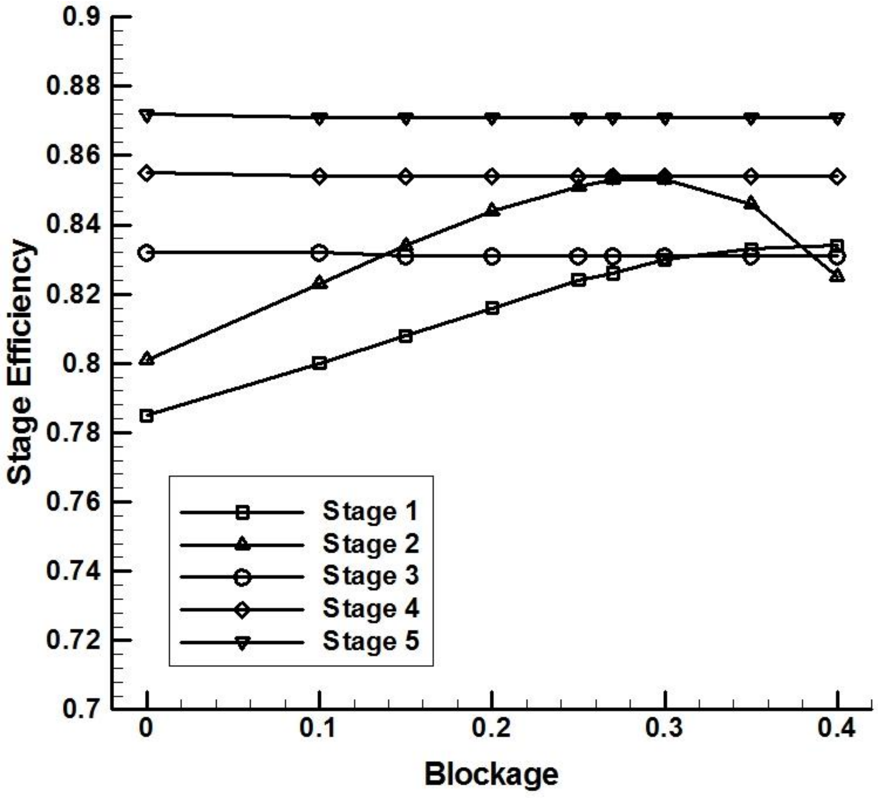
Effect of Additional Blockage on Stage Efficiency and Rotor Relative Velocity Ratio, Blockage in Stage 2

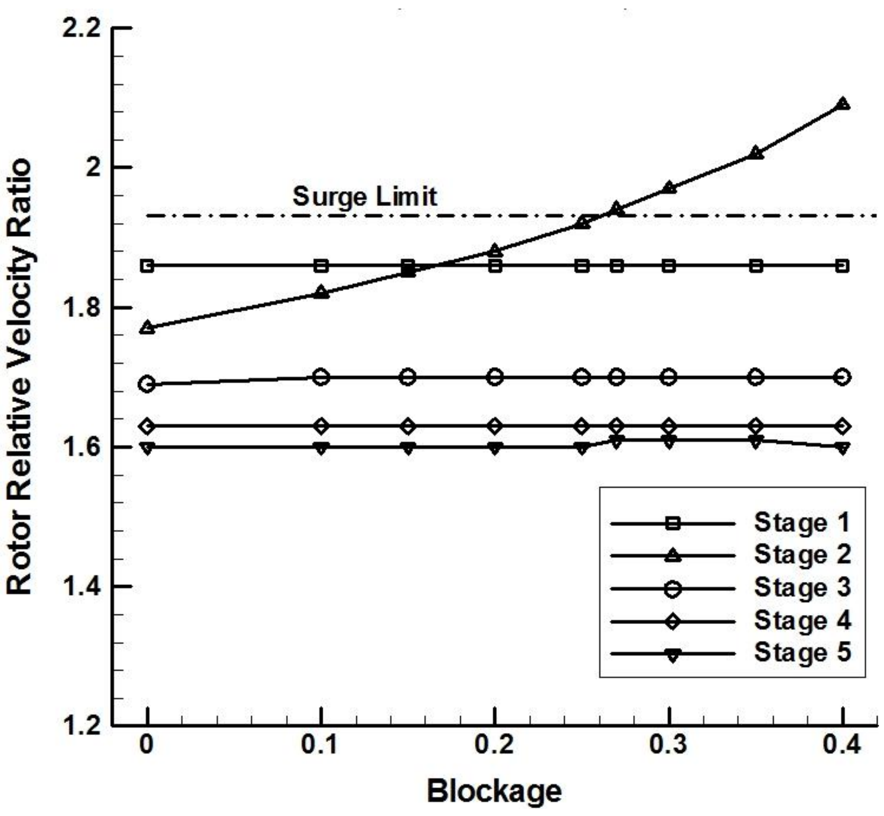
Inlet Mach .49, Altitude 20K ft, Thrust 10%



Effect of Additional Blockage on Stage Efficiency and Rotor Relative Velocity Ratio, Blockage in Stage 1

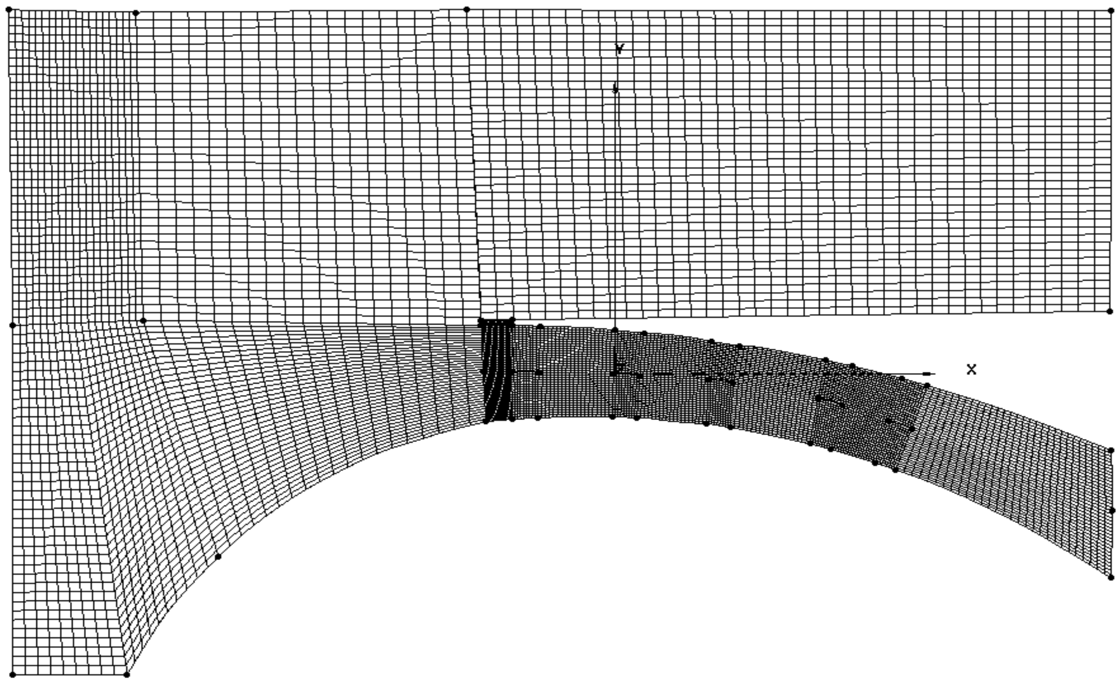
Inlet Mach .45, Altitude 15K ft, Thrust 10%





Estimation of Ice Accretion

Computational Grid of Fan and LPC for analysis with GlennICE Accretion Code



The blade-row by blade-row flow field estimated by the NPSS - COMDES is provided to the GlennICE code for refined estimation of ice accretion.

To be continued in the following session on "Engine Icing Accretion Simulation".

Summary and Conclusions

- A computational tool is being developed to estimate effects of compressor stator vane ice accretion on the performance of the LPC in an engine system environment.
- The current tool consists of an engine thermodynamic cycle model, and a compressor mean line flow analysis model.
- The engine system model and the compressor flow analysis models have been tightly coupled.
- The tool has been applied to a notional gas turbine engine to parametrically assess the sensitivity of engine performance to blockage due to ice accretion. The analysis was conducted over a flight trajectory typical of a commercial aircraft.
- The assumption of static temperature alone as an early indicator of the onset of ice accretion is not sufficient by itself. A model based on relative humidity and wet bulb temperature may be necessary for an improved early estimation of initiation of ice accretion.