High Temperature, High AN2 Last Stage Blade for 65% Efficiency

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Agenda

- Background on the PI
- What's a Last Stage Blade
- What's AN^2
- Project Overview
- Task 2 Overview
- IP Landscape and Next Steps

Background of the PI…

GE Experience... accomplished Technical Leader

Testing

Technology Teams
Telemetry Systems
Clearance Probes
Laser Probes
Combustion Cameras

Prototype Validation

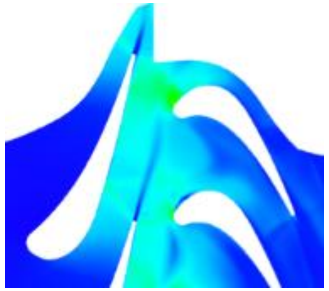
Field Support

Innovation for Validation...
Laser probes for output validation

Aeromechanics

Predictive Tools
Frequency
Mode Shape
Damping
Stimulus Strength

Collaboration
Power
Aviation
Research Center

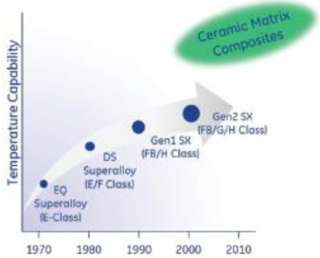


First successful pretest prediction

CMC

Advanced Technology Organization

Leading design, fab & test teams
Shrouds
Nozzles
Blades

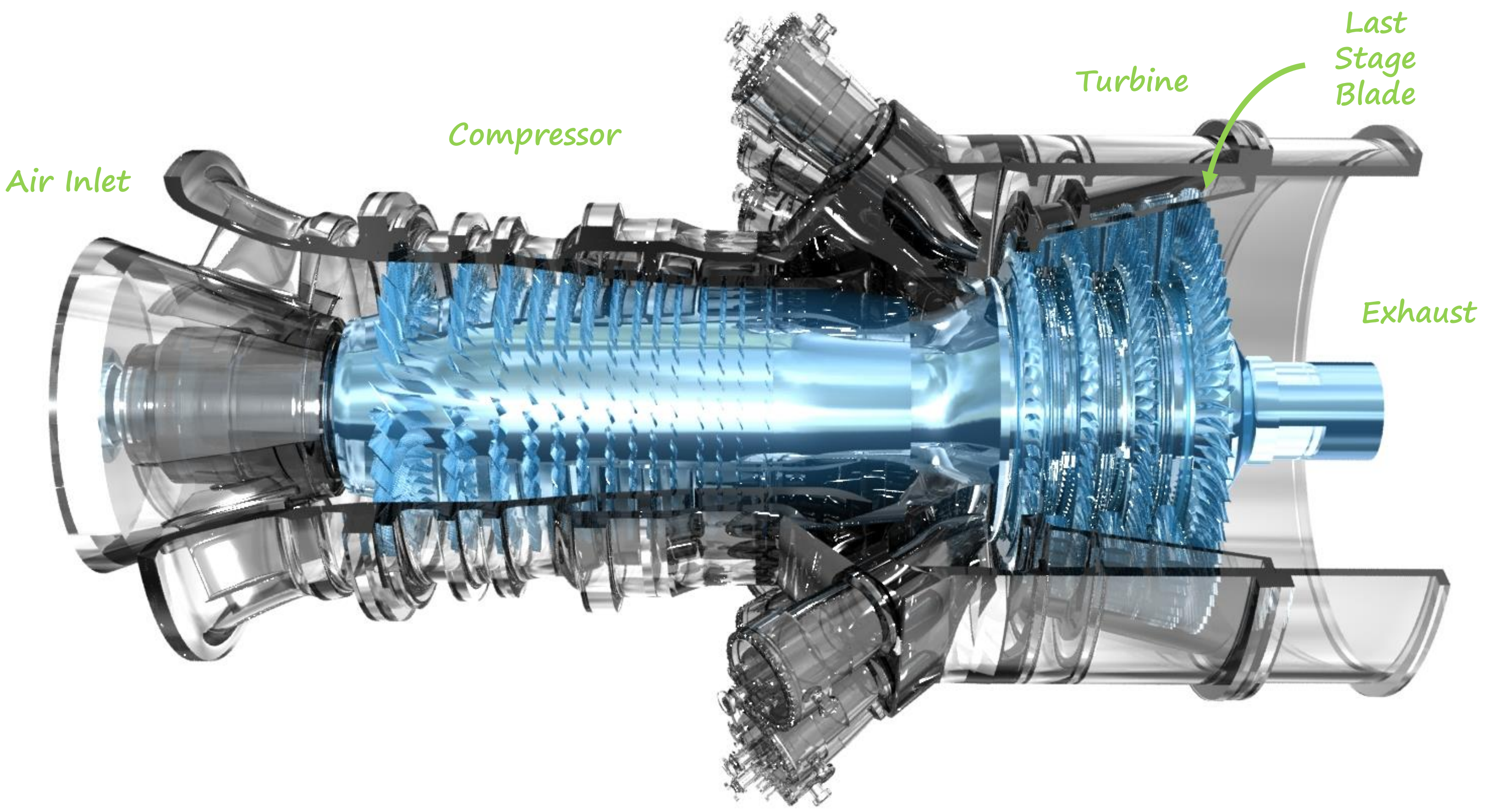


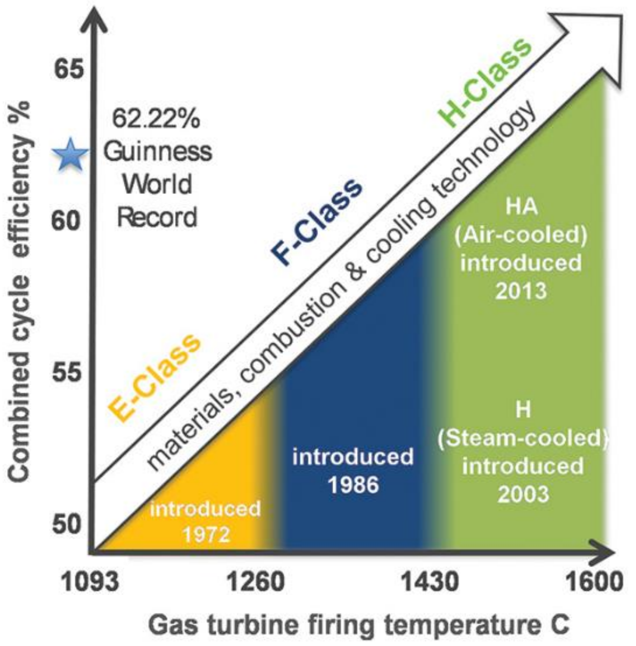
First Product Offering

Leading DoE Contracts
Delivering impactful results...

What’s a Last Stage Blade?

Industrial Gas Turbine





HA class turbine blades seeing higher flow-path temperatures

Basic Design Attributes

Energy Extraction

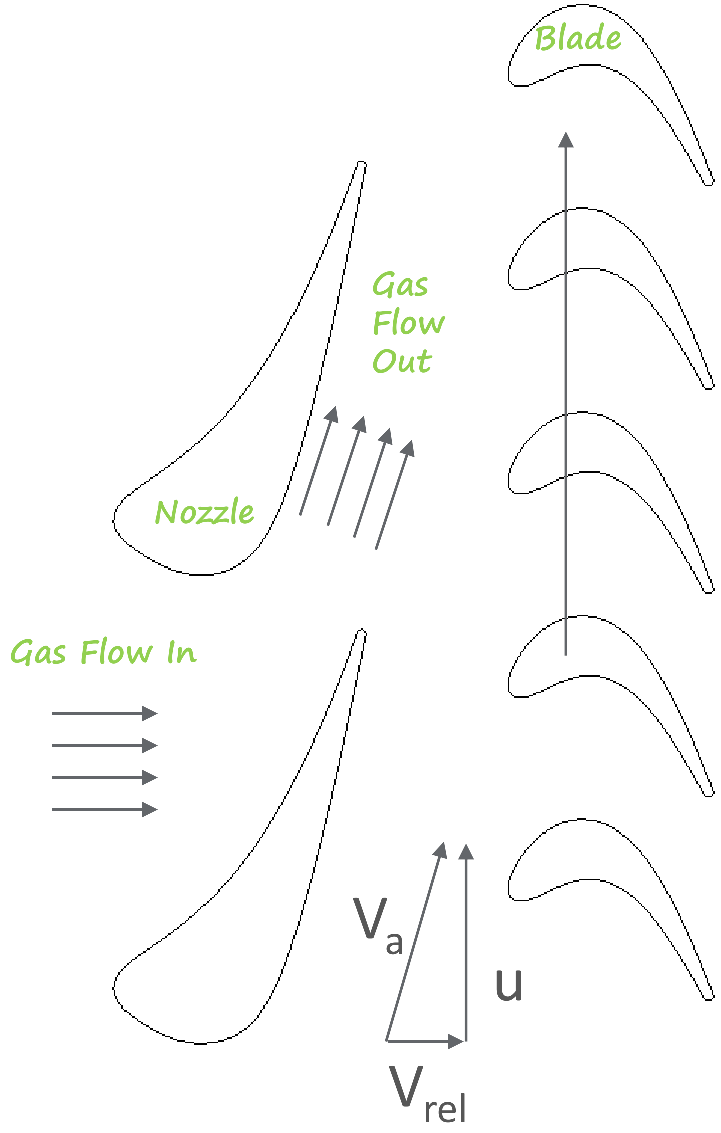
Convert the high temperature, pressure and velocity combustion flow from the upstream nozzle into rotational energy

Mounting

Blades are typically cantilevered from the wheel attachment. Large blades may employ interconnecting shrouds to improve structural rigidity.

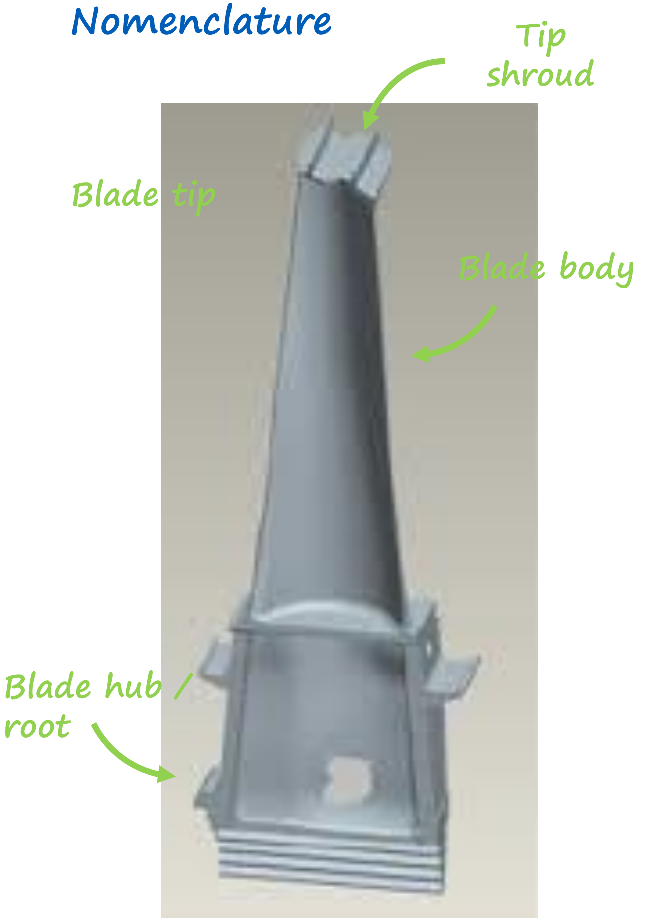
Cooling

- Cooling the blade structure to acceptable bulk temperatures
- More cooling directly reduces engine performance.

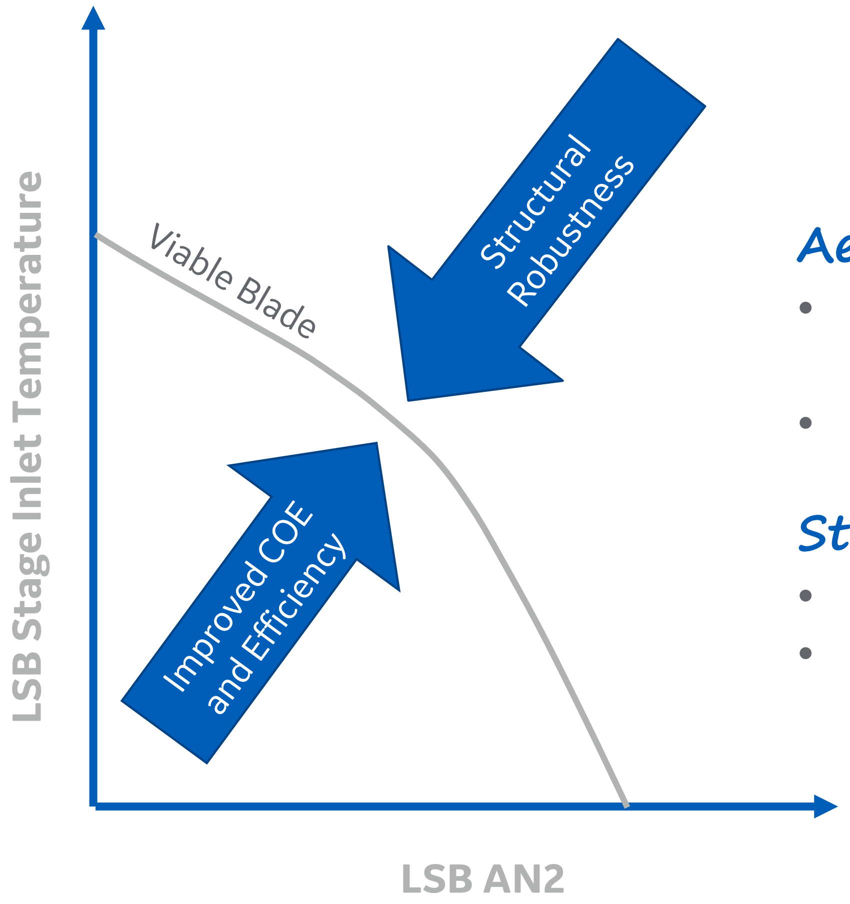


Nomenclature and Challenge

Nomenclature



LSB – Last Stage Blade



COE – Cost of Electricity

Aeromechanics

- Natural mode response, 1F, 1T…
- Aeroelastic instability

Structural Quality

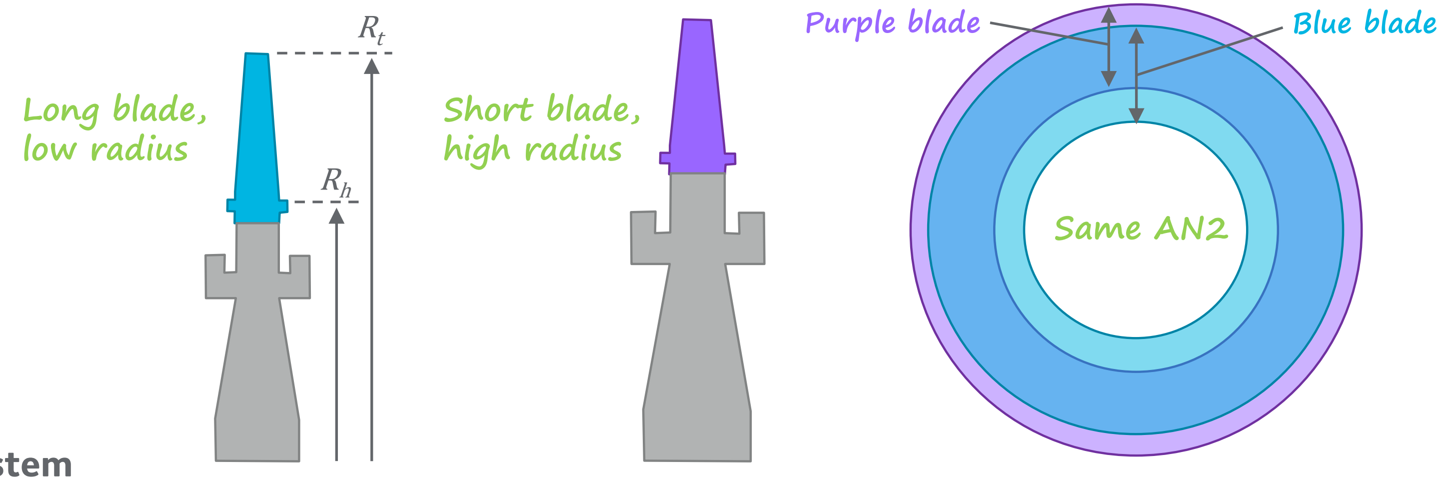
- Low Cycle Fatigue
- Creep

What’s a AN^2?

What's AN²?

The AN2 of a rotating turbine blade is a term that the industry uses to characterize blade size and flow capability. It is proportional to the annulus area multiplied by the rotational speed squared:

$$AN2 = \frac{\pi\left(R_t^2 - R_h^2\right)RPM^2}{1 \times 10^9}$$



It is an indicator of:

- **The maximum air flow capability of the turbine system**
  - Airflow is directly correlated with total combined cycle plant output. In general, the larger the AN2, the larger the power output, and the lower the overall GT $/kw and COE.

- **The aerodynamic efficiency of the turbine system**
  - Larger annulus area reduces Mach no thereby increasing stage & diffuser aerodynamic efficiency

- **The level of mechanical and aeromechanical design challenge. For a given AN2:**
  - Longer blade length (R_t-R_h) will result in lower blade and rotor stresses, but lower blade stiffness / frequencies
  - Shorter blade positioned at a higher radius will have increased stresses, but higher blade stiffness / frequencies

LSB AN2 is a major driver of gas turbine and combined cycle plant economics

Program Overview

Project Objectives & Technical Approach

Objective

Develop blade mechanical damping technology and other vibration management strategies to advance the state-of-the art IGT LSB capability.

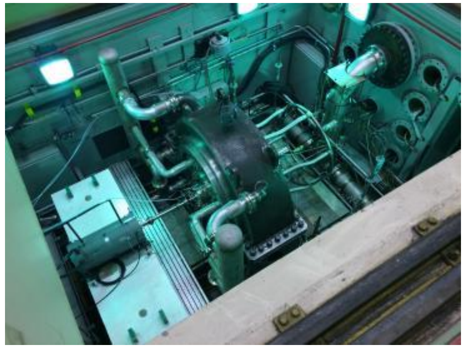
Technical Approach

Phase I - Analytical

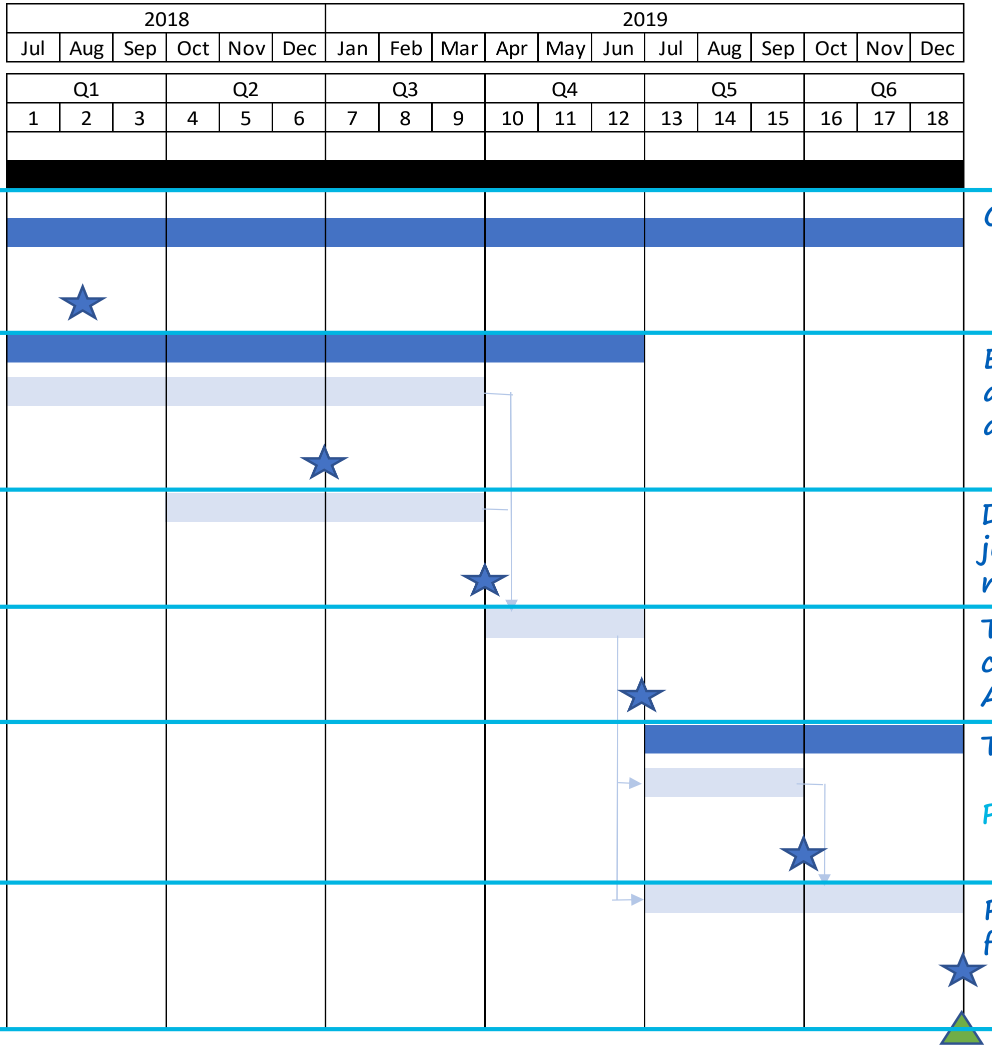
- Develop new damper designs and strategies to maximize damping effectiveness
- Improve understanding of non-synchronous vibration and mitigation strategies
- Perform system trades…cooling requirements, aero efficiency, exit Ma, cost, etc.
- Down-select viable blade-damper solutions on effectiveness, durability, manufacturability, etc.
- Develop Phase II test plans

Phase II – Test & Learn

- Wheelbox testing
- Damper wear
- Manufacturing trials
- Etc…



Project Structure & Schedule



OVERALL PHASE I PROJECT

Task 1	**Project Management**	Ongoing
	Milestone 1.1.1 Update project management plan	
Task 2	**Conceptual Design & Feasibility**	Establish mechanical, aeromechanical, and aerodamping capabilities of alternative blade architectures.
Subtask 2.1	Blade Architecture	
	Milestone 2.1.1 Aero/mechanical feasibility assessment	
Subtask 2.2	Damping Architecture	Develop advanced damper concepts, perform jugulars, and rank. Conceptual modeling, cost, & manufacturability assessments.
	Milestone 2.2.1 Impact of damping techs & strategies	
Subtask 2.3	System Concept	Tying it together…combine leading damper concepts with 1-2 blade designs with 3D analysis. Assess damper effectiveness and design feasibility.
	Milestone 2.3.1 Establish AN2, TTrel entitlement & down-select	
Task 3	**Technology Maturation and Test Plan**	Test rig and hardware concept design & costing
Subtask 3.1	Preliminary Design	Prepare scope & cost for Phase II proposal
	Milestone 3.1.1 Preliminary hardware definition	
Subtask 3.2	Test Plan	Phase II test planning…rig builds, run plans, facility requirements, etc…
	Milestone 3.2.1 Concept test plan completed	
	Phase I Go/No-Go (to proceed to Phase II)	

Project Risk Management

Risk Description	Type of risk	Likelihood	Impact	Risk Management (mitigation and response strategies)
LSB blade-rotor system unable to mechanically achieve >=Target AN2 and TTrel	Technical	Low	Medium	Investigate impact of weight reduction strategies (shroud elimination / reduction, higher strength materials, cooling, hollow cavities, etc.)
LSB blade-rotor system unable to aeromechanically achieve >= Target AN2 and TTrel	Technical	Medium	Medium	Investigate impact of designs and technologies that result in increased stiffness and damping effectiveness (count optimization, core, Tm/C, mistuning, novel damping concepts, etc.).
Design elements necessary for Target AN2 and Ttrel result in a loss of turbine performance	Technical	Low	Low	Understand performance degradation contributions of blade design elements (cooling requirements, clearances, etc.) and trade against benefits from AN2 & TIT/Ttrel
Damper solution(s) do not satisfy HCF design requirements (damper effectiveness)	Technical	Medium	Medium	Understand damping requirements for various blade architectures and eliminate non viable options. Validate in Phase II testing.
Damper solution(s) are not robust to high vibration levels or HD GT duty cycle (damper wear)	Technical	Medium	Medium	Leverage current understanding of wear couples. Validate in Phase II testing.
Fidelity of conceptual analysis cannot accurately predict SV & NSV phenomena	Technical	Medium	Medium	Understand and report prediction uncertainty in concept screening (Task 2.0). Improve tools or approach if needed. Confirm design predictions with higher fidelity analysis in Task 3.0.
Availability of team members and experts to complete program milestones	Schedule	Low	Low	Phase I scope is small for an 18 month program schedule. GEP / GEGR to manage the team resources across all engineering demands to insure the DOE milestone obligations are met.

Technical risks are manageable through analytical work, concept ranking, design trades, and Phase II testing.

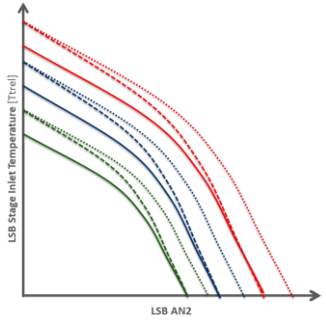
Task 2 Overview

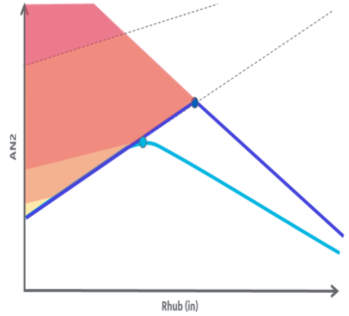
Blade Architecture Studies

Blade & Rotor Mechanical

"How big can I go?"

- 1D blade sizing…section stress analysis vs. design requirements
- Cooling requirements
- Space sweeping design-of-experiments
- 1D wheel sizing, application of system & manufacturing constraints

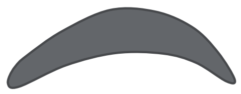


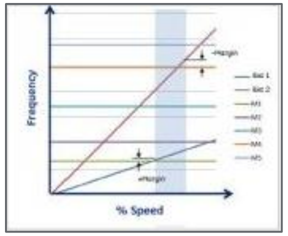


Aeromechanics

"Does frequency avoidance limit my design space? What are the mode shapes?"

- 3D blade design…CFD and FEA analysis
- Modal frequency and modal shape prediction. Margin to design reqt's.
- Design trades…shroud location, count optimization, core, Tm/C, etc.





Aeroelasticity

- Establish stability & margin of design options to non-synchronous vibration
- Understand impact of mistuning

"Is the blade susceptible to flutter or rotating stall?"

Mechanical, aeromechanical, and aerodamping characteristics establish blade damping requirements.

Damping Architecture Studies

Concept Identification & IP Mapping

- Identify viable design concepts that improve mechanical damping capability of shrouded and shroudless blade designs
- Understand novelty and intellectual property coverage

"What is the concept? Is it novel or free to practice?"

Concept Development & Design

- Jugular analysis using advanced FEA methods
- Identification of relevant design parameters
- Ranking & down-select on multiple criteria… Q reduction, weight, cost, etc.

"How capable is the concept and what are the important design parameters?"

Development of novel damping concepts is essential to LSB temperature & AN2 growth

System Studies

Blade-Damper solutions

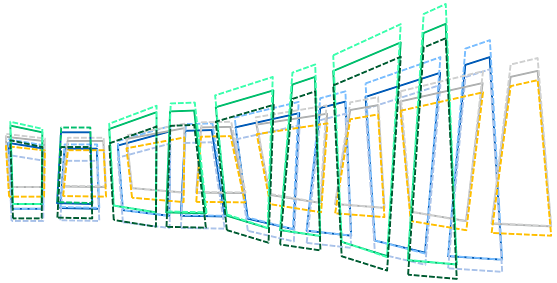
- Combine leading damper concepts with 1-2 blade designs with 3D analysis
- Down-select viable blade-damper solutions
  - effectiveness,
  - durability,
  - manufacturability, etc.

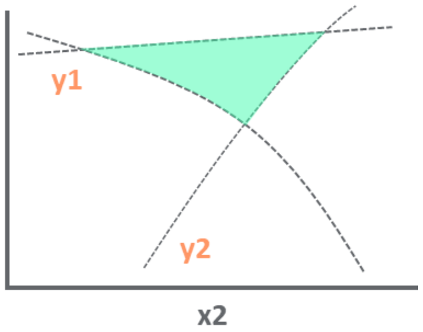
"Can we meet our design objectives and requirement?"

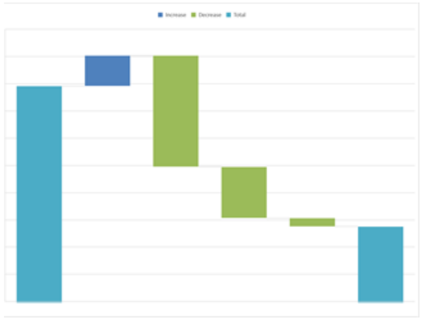
Blade Architecture Trades

- Perform system trades…
  - cooling requirements,
  - aero efficiency,
  - exit Ma,
  - manufacturability,
  - cost, etc.

"What's the best approach for a large, hot LSB?"







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Identify viable design concepts that maximize gas turbine and combined cycle plant economics.

IP Landscape
and
Next Steps

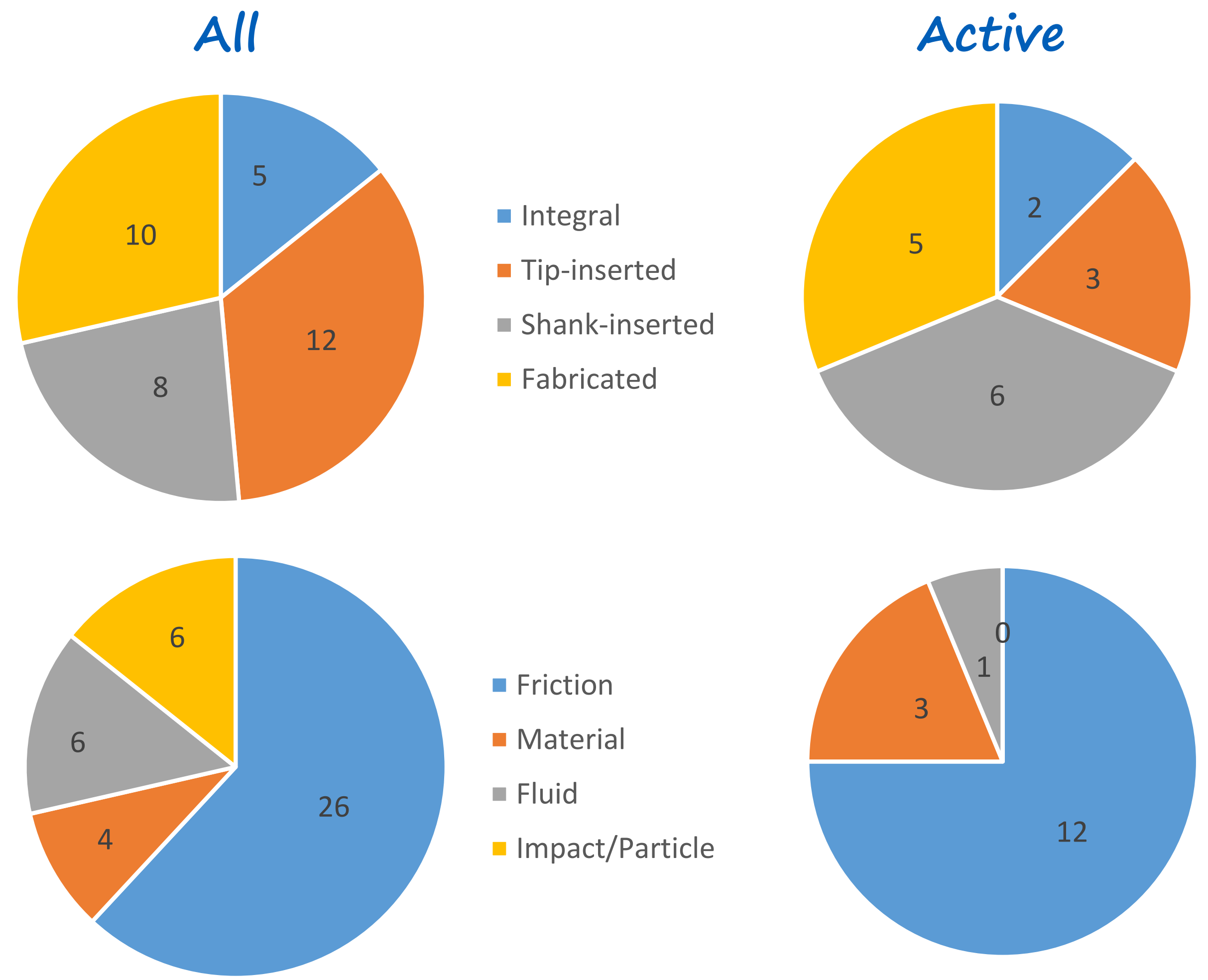
Internal damping IP Landscape

Categories (Assembly and Manufacturing)

- Integral dampers (printed or cast in place)
- Tip inserted dampers
- Shank inserted dampers
- Fabricated blade+damper

Categories (Damping Technology)

- Friction damping
- Material damping
- Fluid damping
- Particle/Impact damping



Tip/Shank inserted internal friction dampers most common. Relatively open landscape for integral dampers.

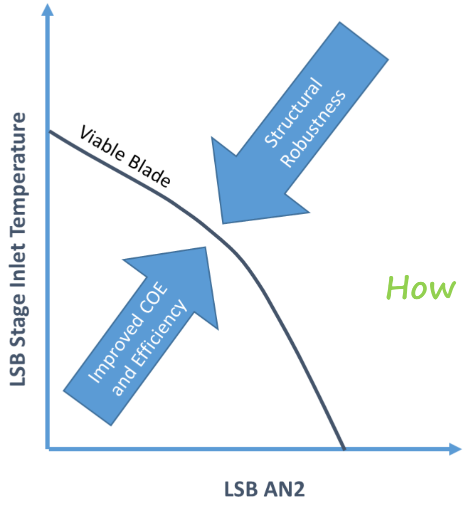
Next steps

Blade architecture

- Blade and Rotor design space definition
  - Understand AN2 and temperature capability for different blade + rotor candidates from static mechanical calculations
- Aeromechanical feasibility assessment for different blade architectures
  - modal frequency avoidance
  - flutter capability
- Establish damping targets for new blade architectures

Damping architecture

- Develop concepts for assessment
- Evaluate analytically
- Down-select the most promising concepts for development and test



How far can we go?

Q&A
Discussion