Advanced Airfoils for Efficient CHP Systems

Project Overview

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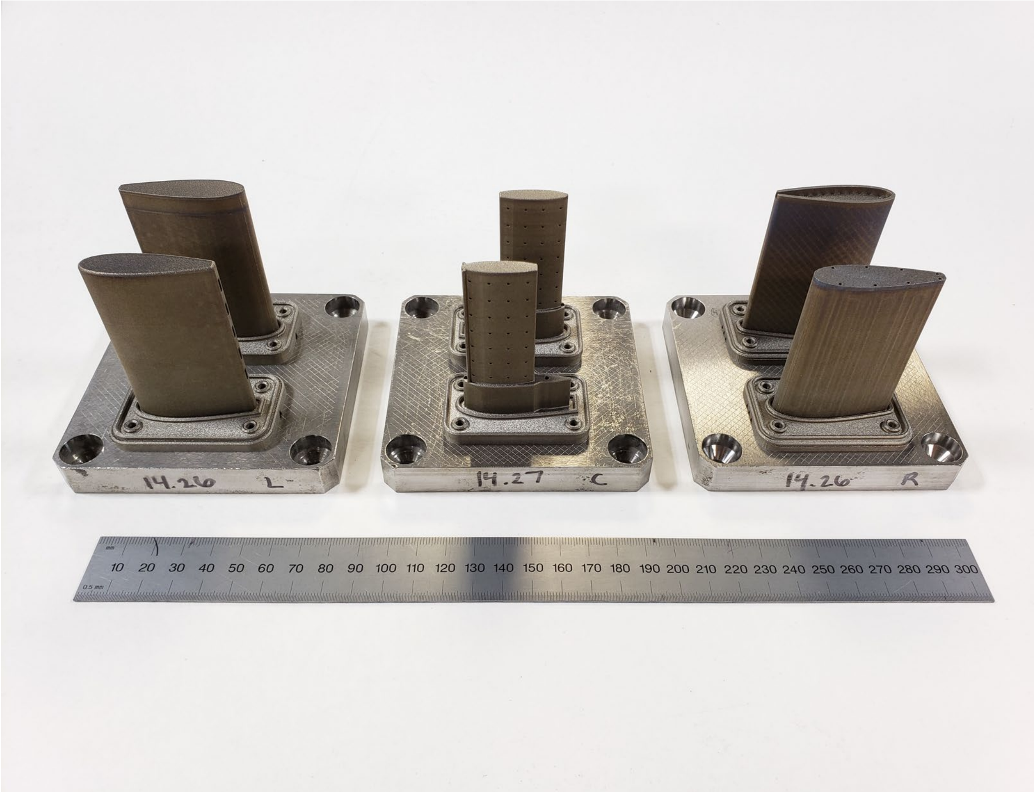
NATIONAL ENERGY TECHNOLOGY LABORATORY



Presentation Overview/Outline

Advanced Airfoils for CHP Applications

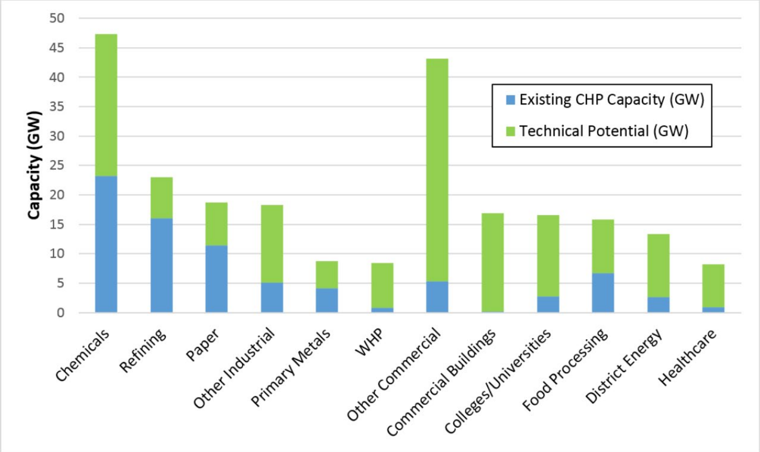
Motivation

- Current Combined Heat and Power (CHP) market in U.S.
- Goals/objectives
- Environmental and economic benefits

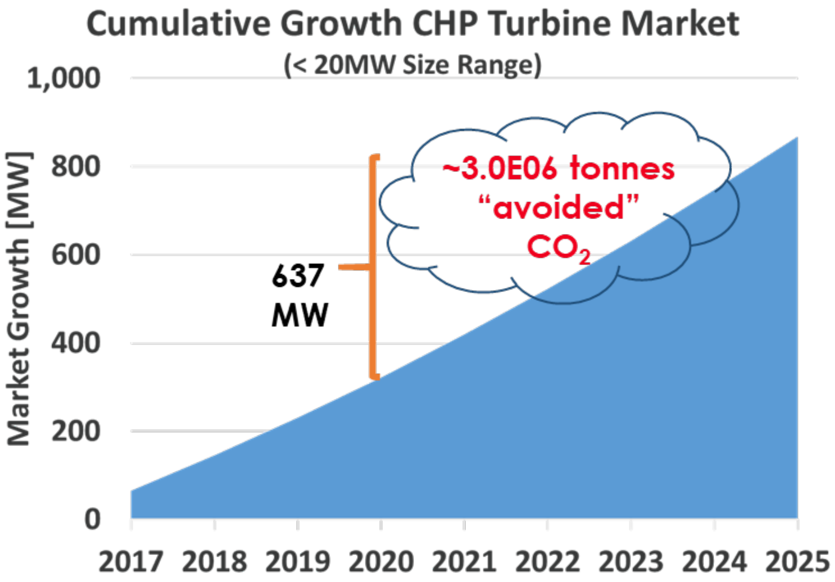
Technical Challenges/Approach

Summary of results and project status

- Baseline CHP system analysis/energy storage analysis
- Design/build/test airfoil cooling configurations
  - Baseline (1st stage blades & vanes)
  - Advanced concepts
- Oxide dispersion strengthened powder enhancements



U.S. DOE CHP Deployment Program, 2016.



Project Goals and Benefits

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Goals:

- To increase 1st stage turbine inlet temperature by 100 °C for baseline 5-10 MW CHP turbine applications
  - Advanced materials + AM + Advanced Cooling Designs
- Transfer technologies to industry in Phase 2 effort

Benefits:

- Reduce payback period for CHP plants
  - Power increased by 20%
  - Efficiency increased by 2 percentage pts relative to 33% baseline
  - Steam production increased by 10-15%
- Reduce CO_2 emissions and fuel consumption
  - 36% relative to conventional power/boiler configuration
  - 7% relative to baseline CHP plant

Oak Ridge National Laboratory

leidos

West Virginia University

University of Pittsburgh

University of North Dakota

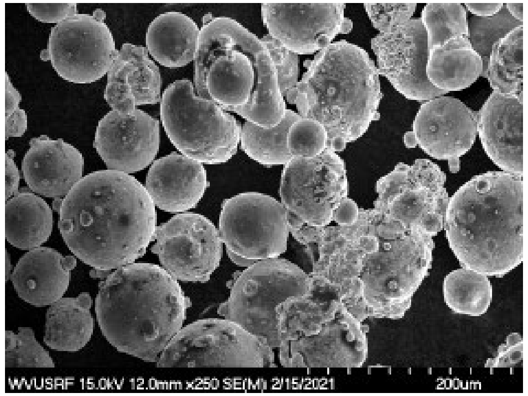
Technical Challenges

Challenge 1

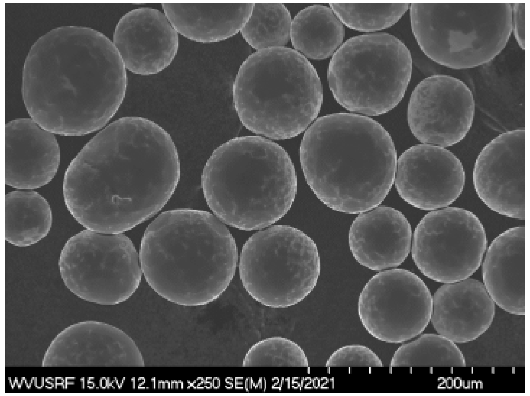
Material properties using AM (Additive Manufacturing) has not been shown to be better than base alloy.

- Oxide dispersion strengthening (ODS) has better high temperature properties
- Traditional AM powder processes cannot produce powders of Y2O3 or Al2O3 because of the high melting points
  - Different approach is needed

As Received Powder



Post-Processed ODS Powder

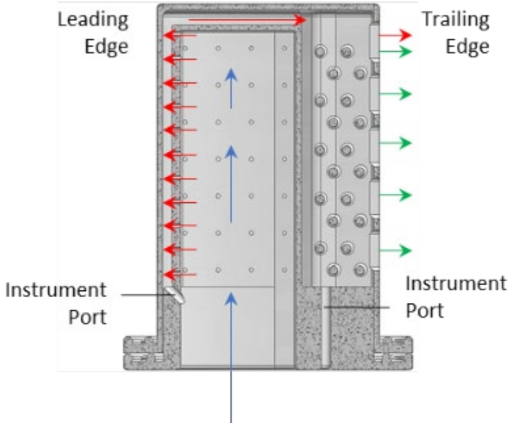


Challenge 2

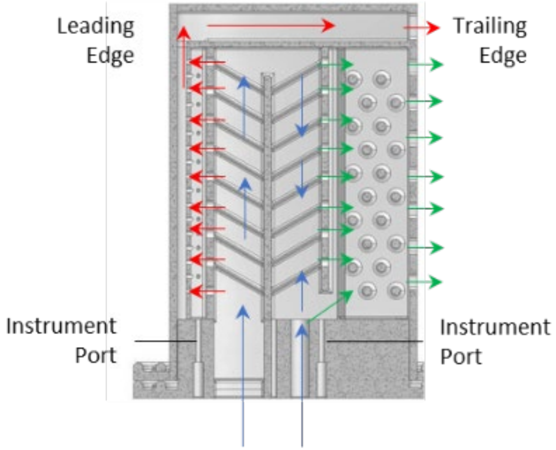
Benefits of proposed cooling architectures cannot be quantified without a common baseline.

- Public data on integrated airfoil cooling are focused on large GT engines and limited
- Test protocols for integrated performance are limited
  - Cooling performance
  - Pressure drop and coolant flow curves

Baseline Vane



Baseline Blade



Three Main Areas of Focus

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System Modeling and Market Benefits

- Baseline (Virtual) engine model
- Benefits and sensitivity studies
- CHP plant interviews
- Energy storage study for CHP plant

Internal Cooling using Additive Manufacturing

- Baseline vane and blade design, build, testing
- Other designs
  - *Lattice*
  - *Micro-channel*
  - *NETL double-wall*
  - Incremental impingement double-wall

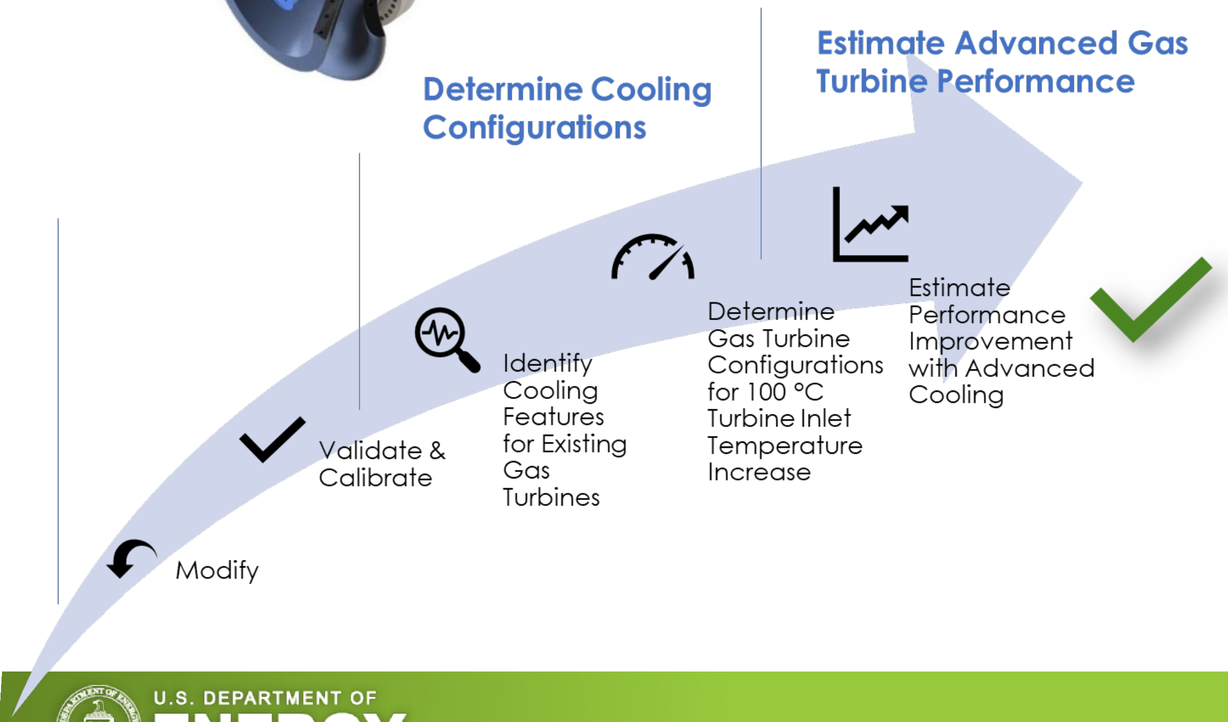
Oxide Dispersion Strengthened AM Materials

- Develop ODS powders for AM
- Fabricate test coupons
- Characterize properties
- IN718 vs ODS718
- M247 vs ODS247

Model for Baseline “Virtual” Gas Turbine

CHP Generic Gas Turbine 2015 Baseline

Source: NETL



- Power Output: 6.1 MW
- Thermal Efficiency: 33.1%
- Exhaust Temperature: 968 °F
- Year of Introduction: 2015
- Simple Cycle CHP Applications
  - 15-Stage Compressor,
  - 4-Stage Turbine

Cooling Specs

- TBC on Stages 1 & 2
- Stage 1 and Stage 2 Internally Cooled

Assessing the Impact of Better Cooling

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		Upgraded Engine		
	Baseline Engine	Baseline Cooling Conf.	6% Increase in Int. Cooling Eff.	13% Increase in Int. Cooling Eff.
Power (kW)	6100	7214	7416	7592
Thermal Efficiency	33.1%	34.0%	34.7%	35.3%
Heat Rate (Btu/kWh)	10208	10026	9829	9669
Exhaust Temperature (°F)	968	989		
Coolant Fraction	9.6%	14.1%	13.5%	12.9%

Test Approach For Internally Cooled Airfoil Testing

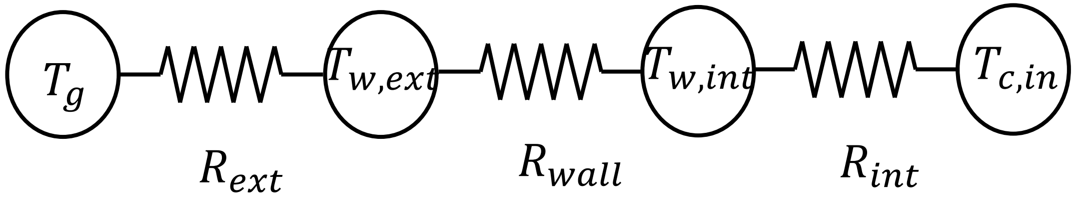
Measure non-dimensional surface temperature, ϕ

Data from Public Engine Model (Uysal et al., 2021)

	Hot Gas Path T_g	Coolant $T_{c,in}$	Max. Metal Temp, $T_{w,ext}$	Overall Cooling Effectiveness
Baseline	1366K	685K	1178K	$\phi > 0.28$
Advanced Target	1466K	685K	1178K	$\phi > 0.42$

Test Conditions

	Hot Gas Path T_g	Coolant $T_{c,in}$	Overall Cooling Effectiveness	Max. Metal Temp, $T_{w,ext}$
Baseline	650	325K	$\phi > 0.28$	559K
Advanced Target	650	325K	$\phi > 0.42$	513K



Overall Cooling Effectiveness

$$\phi = \frac{T_g - T_{w,ext}}{T_g - T_{c,in}} = \frac{R_{ext}}{R_{ext} + R_{wall} + R_{int}}$$

Heat Load Parameter (non-dimensional cooling flow)

$$HLP = \frac{\dot{m}_c c_p}{h_{ext} A_{ext}} = \dot{m}_c c_p R_{ext}$$

Independent variables

- $\dot{m}_c$
- Cooling designs

Dependent variables

- $T_{w,ext}; \phi$

External Thermal Resistance Is Constant

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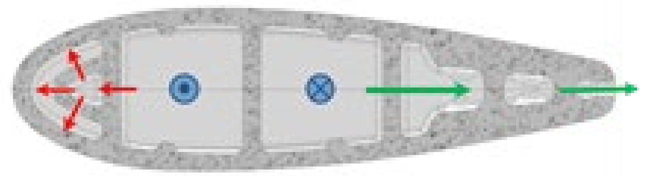
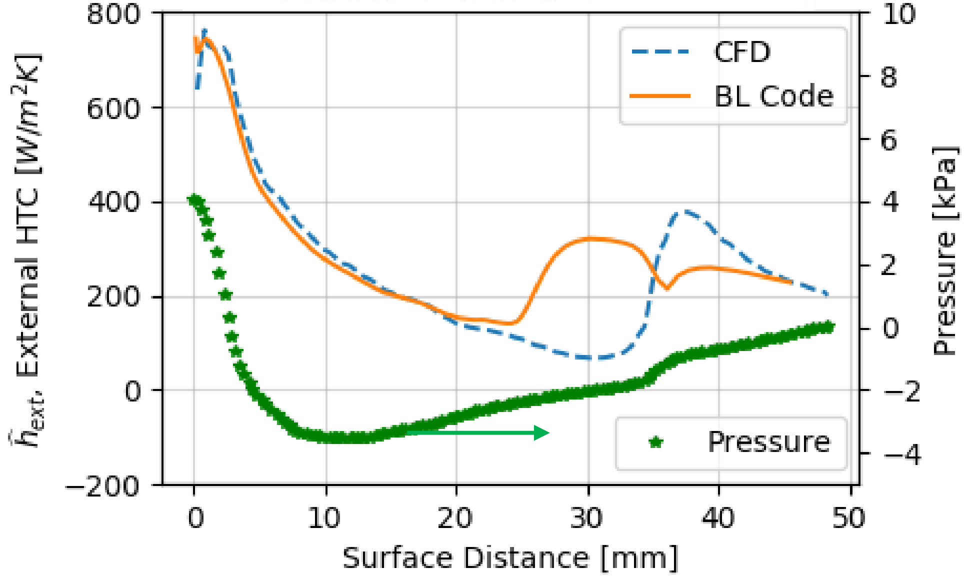
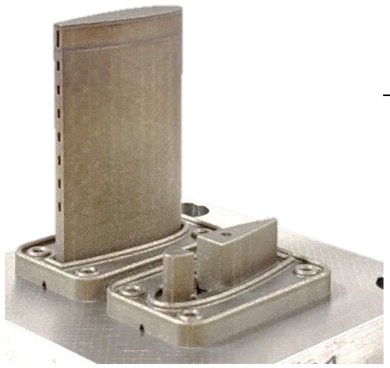
External geometry and conditions

- NACA-0024 external profile
  - Symmetric design for screening different cooling designs
- External test conditions = constant
  - $T_g = 650K; P_g = 0.11\ MPa$
  - $\dot{m}_g = 0.64\ kg/s \rightarrow V_g \cong 120\ m/s$
  - $Ma_g = 0.2$
- Surface roughness







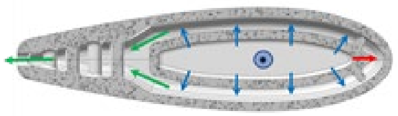
Airfoil Internal Cooling Design	Ra As Received (microns)	Ra After Painting (microns)
Baseline Vane		
Span-wise	5.0 ± 0.6	1.4 ± 0.3
Chord-wise	5.7 ± 1.7	1.5 ± 0.4
Baseline Blade		
Span-wise	3.6 ± 0.8	0.8 ± 0.15
Chord-wise	3.8 ± 0.6	1.0 ± 0.2
NETL Double wall		
Span-wise	1.1 ± 0.2	1.0 ± 0.3
Chord-wise	1.1 ± 0.15	0.7 ± 0.3

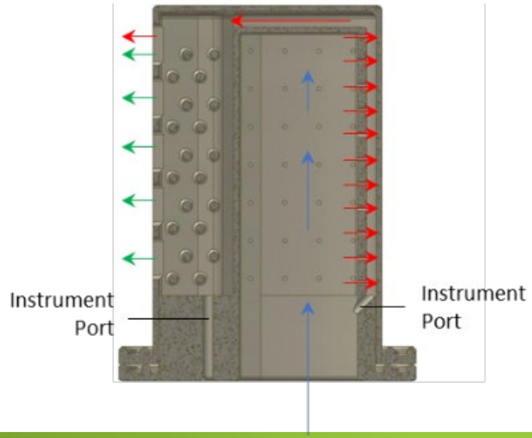
mean $\pm$ 2 standard deviations

Internal Resistance Varies with Design and Flow

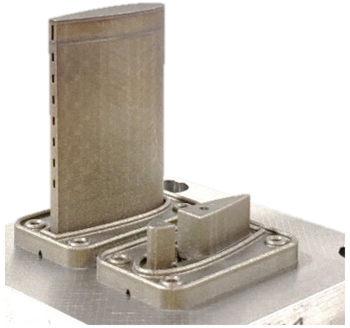
Some of the internal cooling designs tested

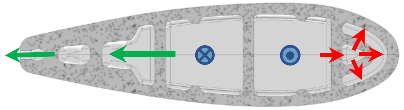
- Baseline Vane

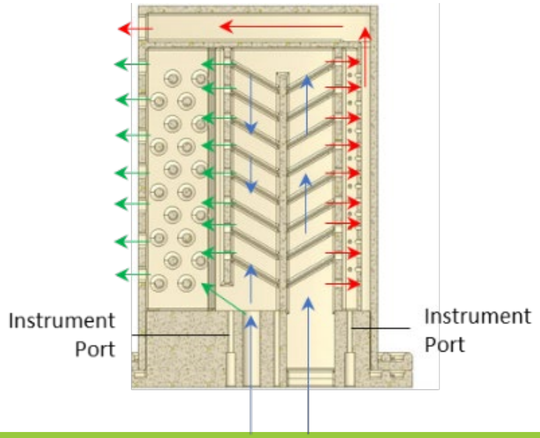




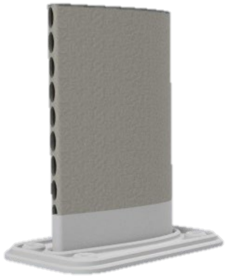
- Baseline Blade

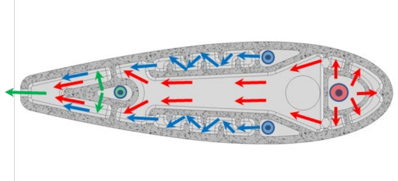




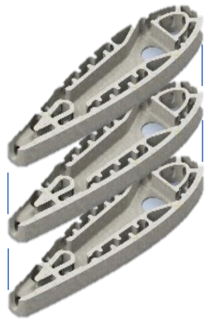


- Stacked double-wall (NETL Design)



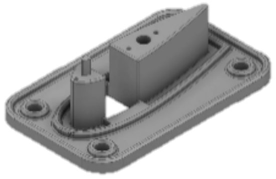


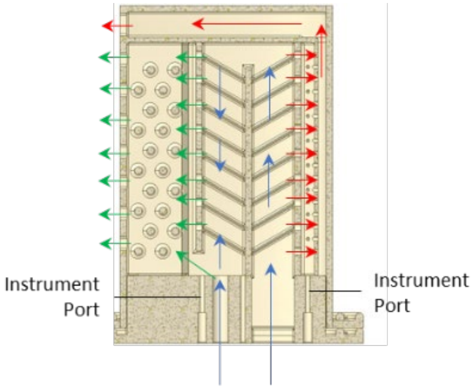
External Surface Removed in CAD

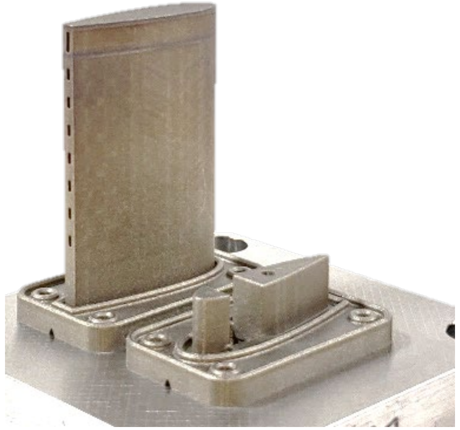


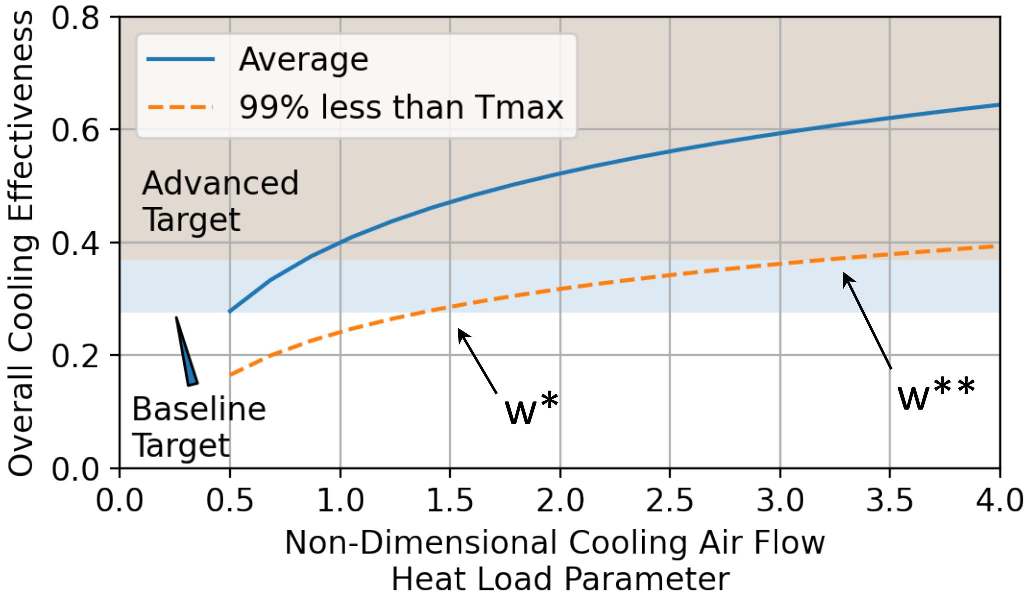
Prototype Airfoil Cooling Results

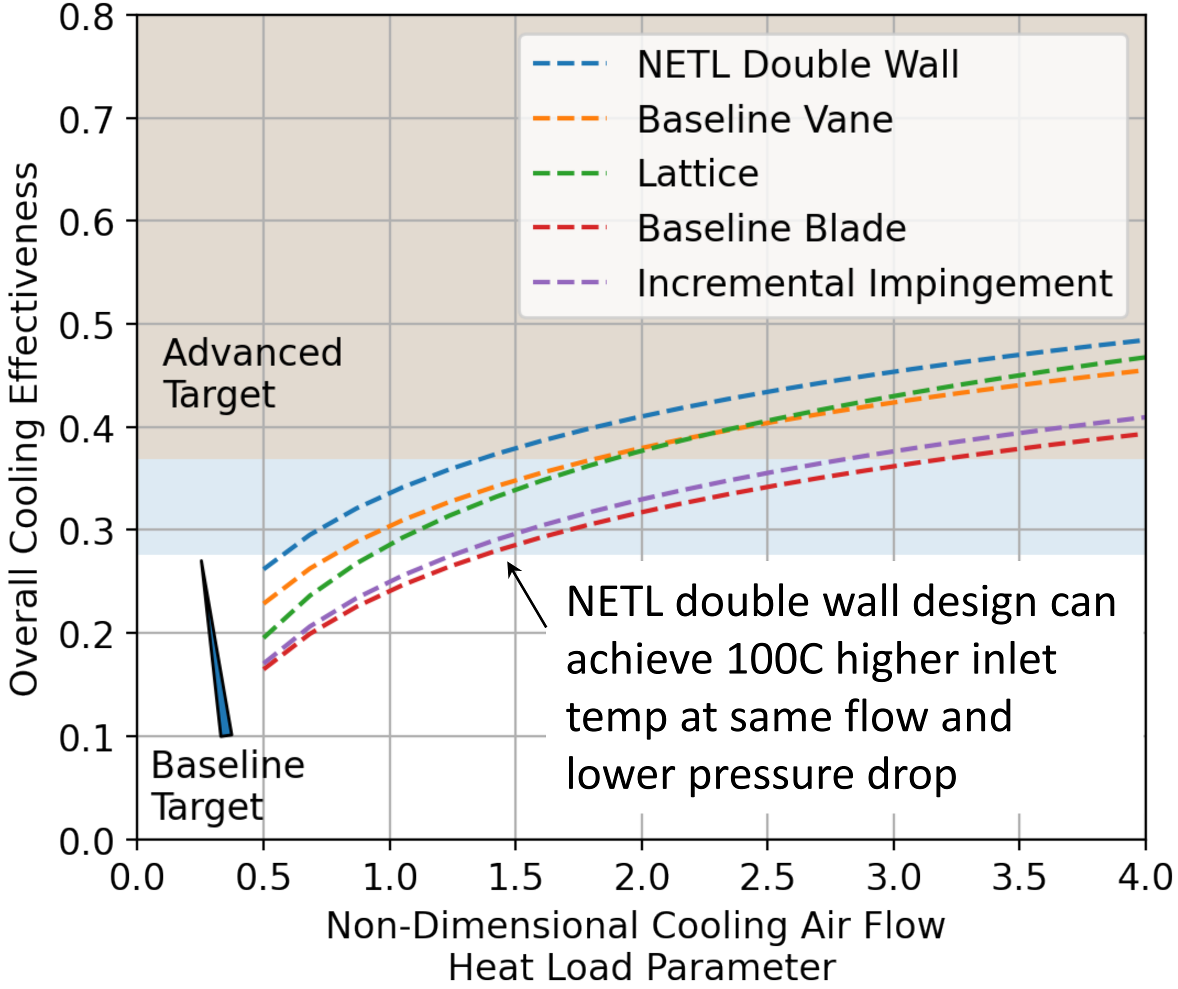
One design is more efficient at low cooling air flows







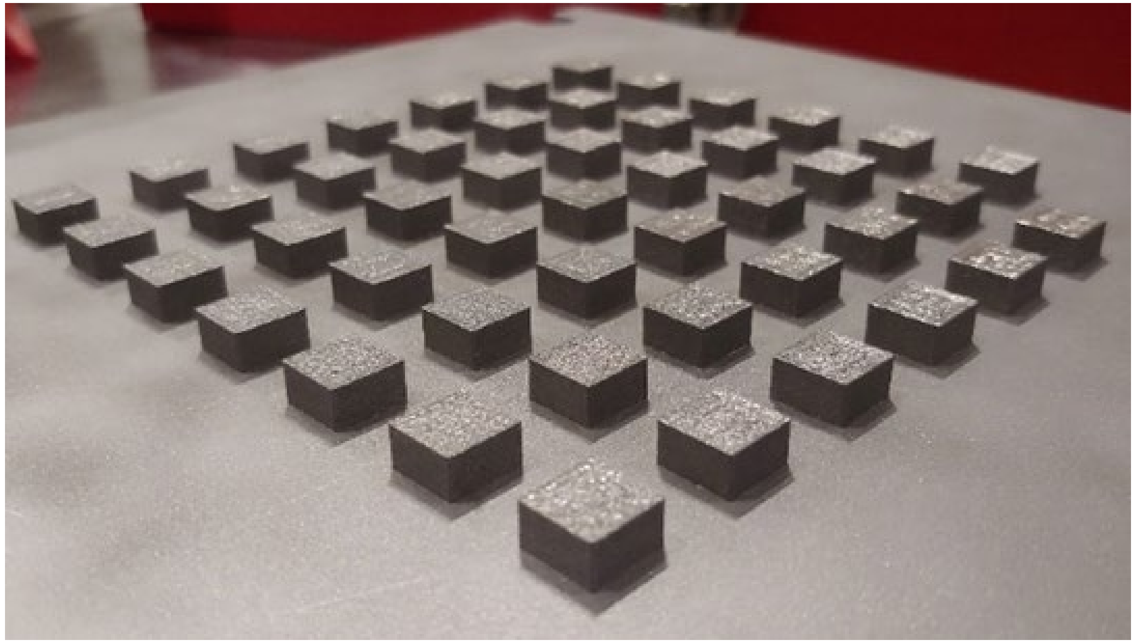




Additive Manufacturing with ODS Powder Processing

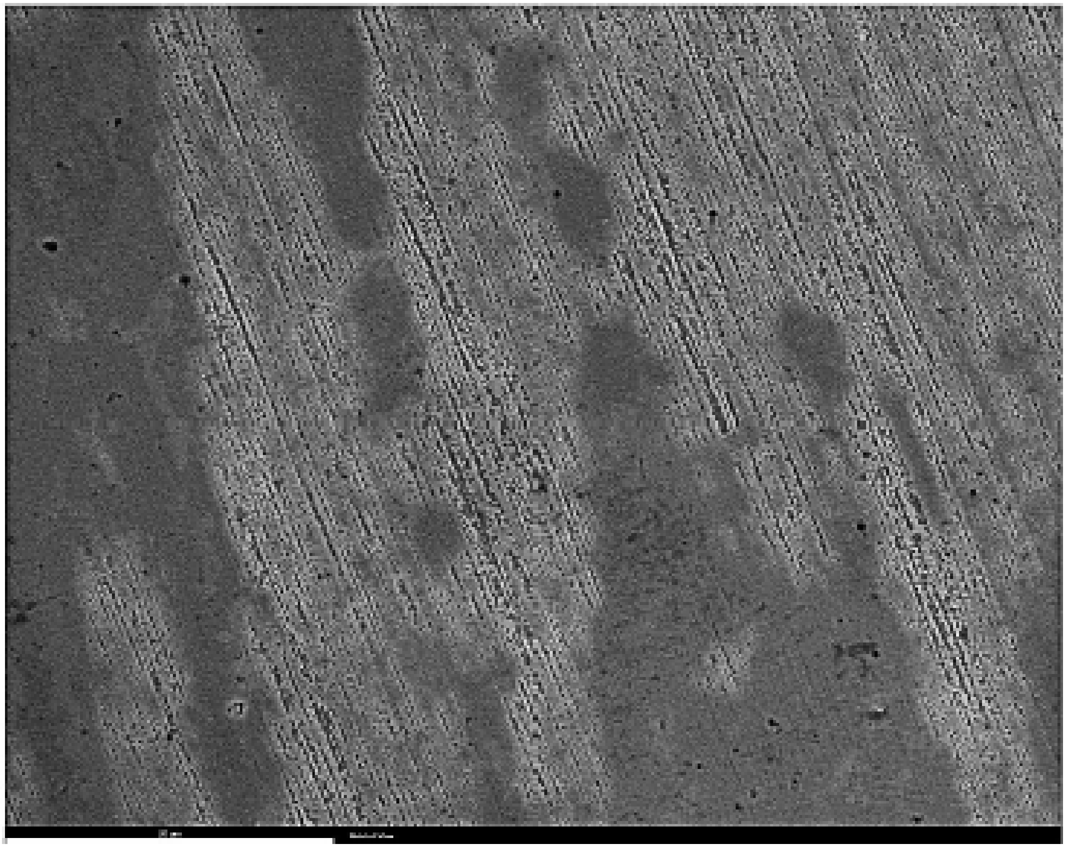
ODS-IN718 samples have been manufactured using 2 approaches

- Direct energy deposition
- Laser powder bed fusion (EOS M290)

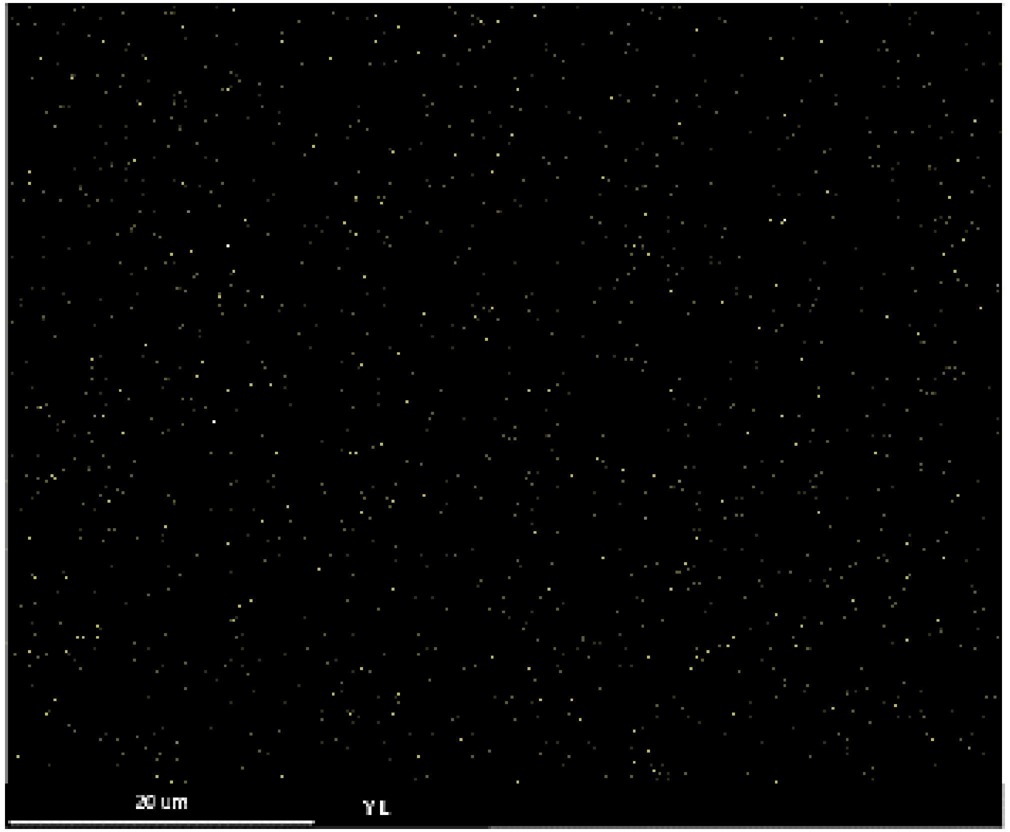


IN718 with 0.5% Y_2O_3 – Uniform distribution

Cross-section and Y-elemental map



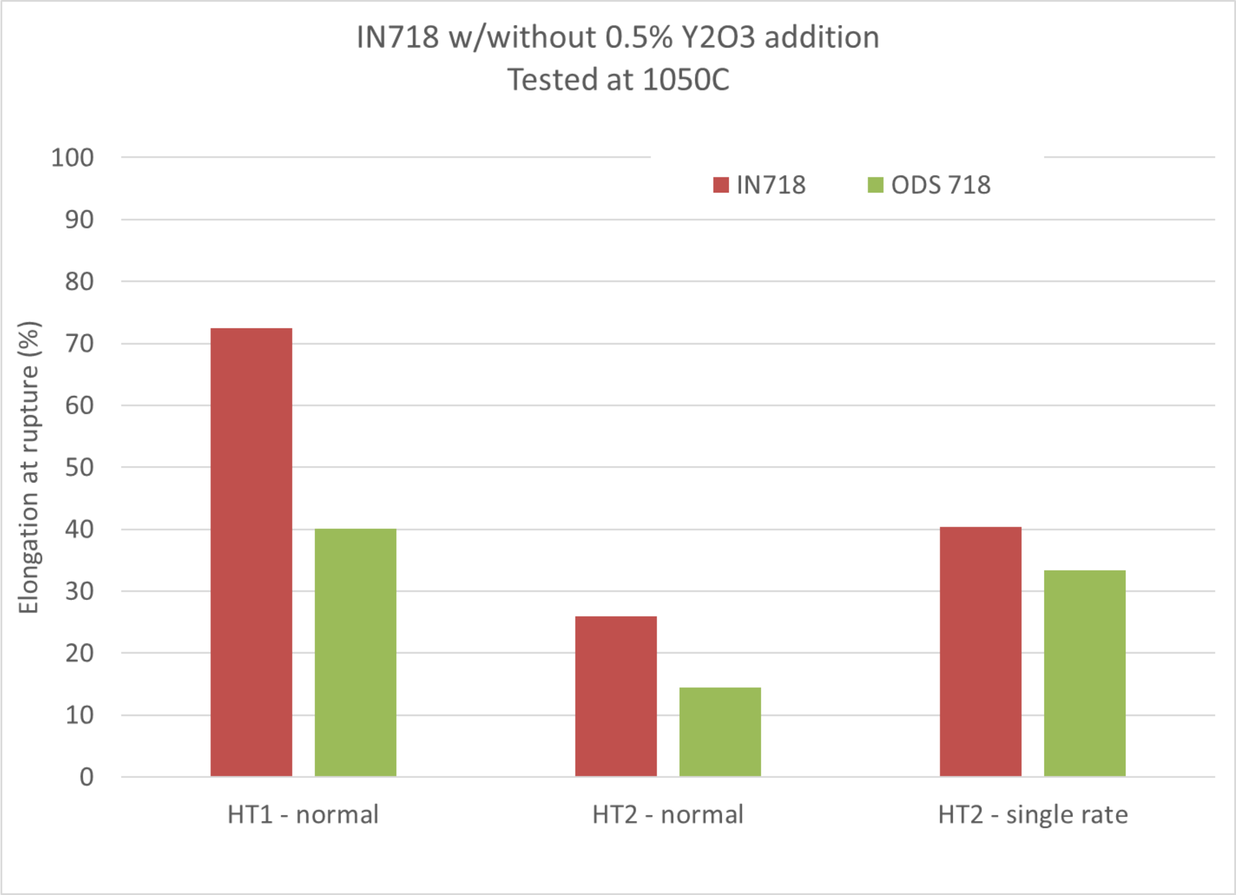
As-printed ODS 718 – cross-section

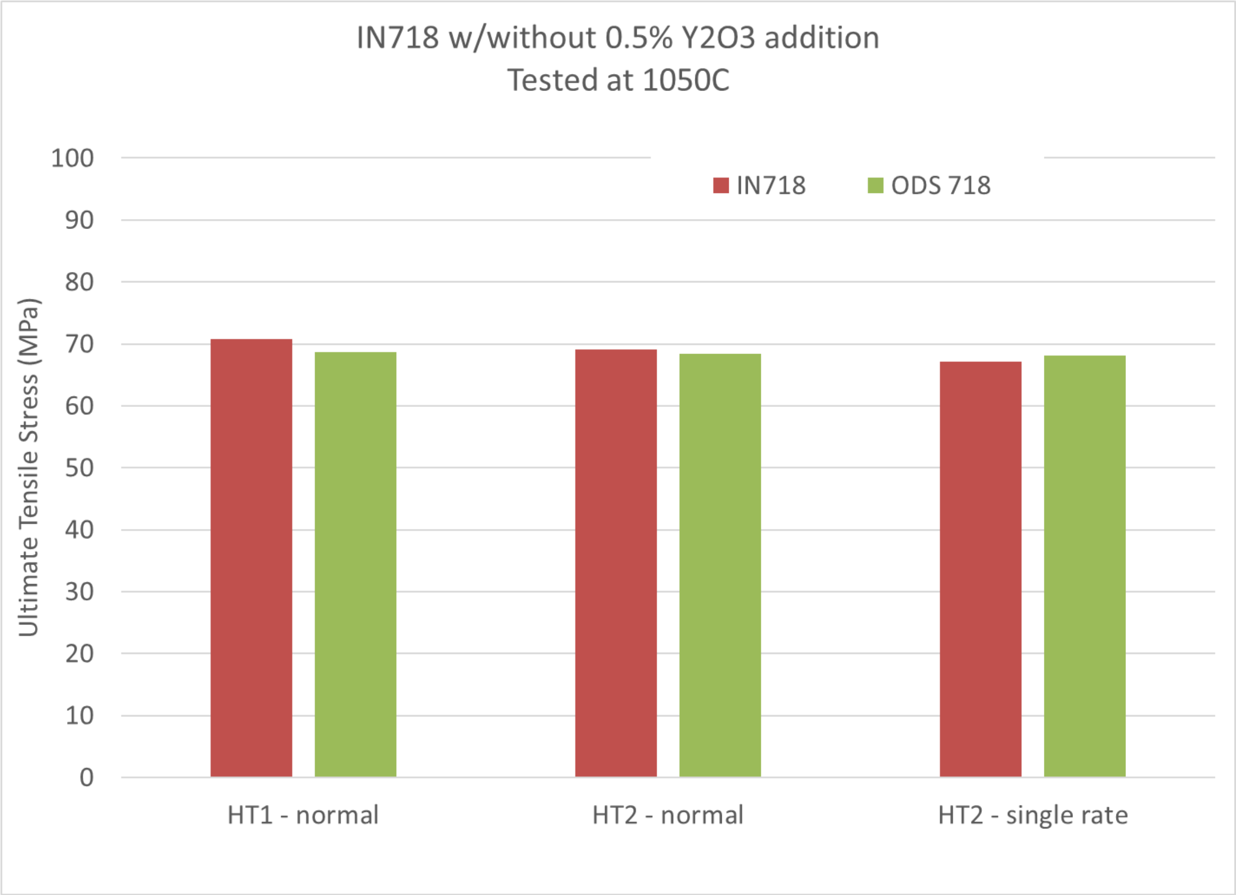


Yttrium is uniformly distributed

0.5% Y_2O_3 addition has little effect on UTS

Need higher Y_2O_3 loading?





Summary

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- Increasing baseline engine firing temperature + improved cooling design
  - 2 percentage point improvement over 33% efficient 5-10 MWe gas turbine
  - Power increase ~ 20%
  - Steam production increase ~ 10%
- Public airfoil cooling concepts (baseline and advanced) designed, built, and tested
  - NETL double-wall concept can achieve advanced cooling target at the same cooling flow and lower pressure drop than baseline blade
- Powder processing method for oxide dispersion strengthen demonstrated for 0.5% Y_2O_3 in IN718
  - Uniform distribution of Y throughout the part
  - Preliminary results and previous work suggest higher Y_2O_3 concentrations are needed
  - ODS M247 powders have also been prepared

Questions, Comments

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