Power and Propulsion: Small Core Advanced Thermal Management Project Overview

November 21, 2022

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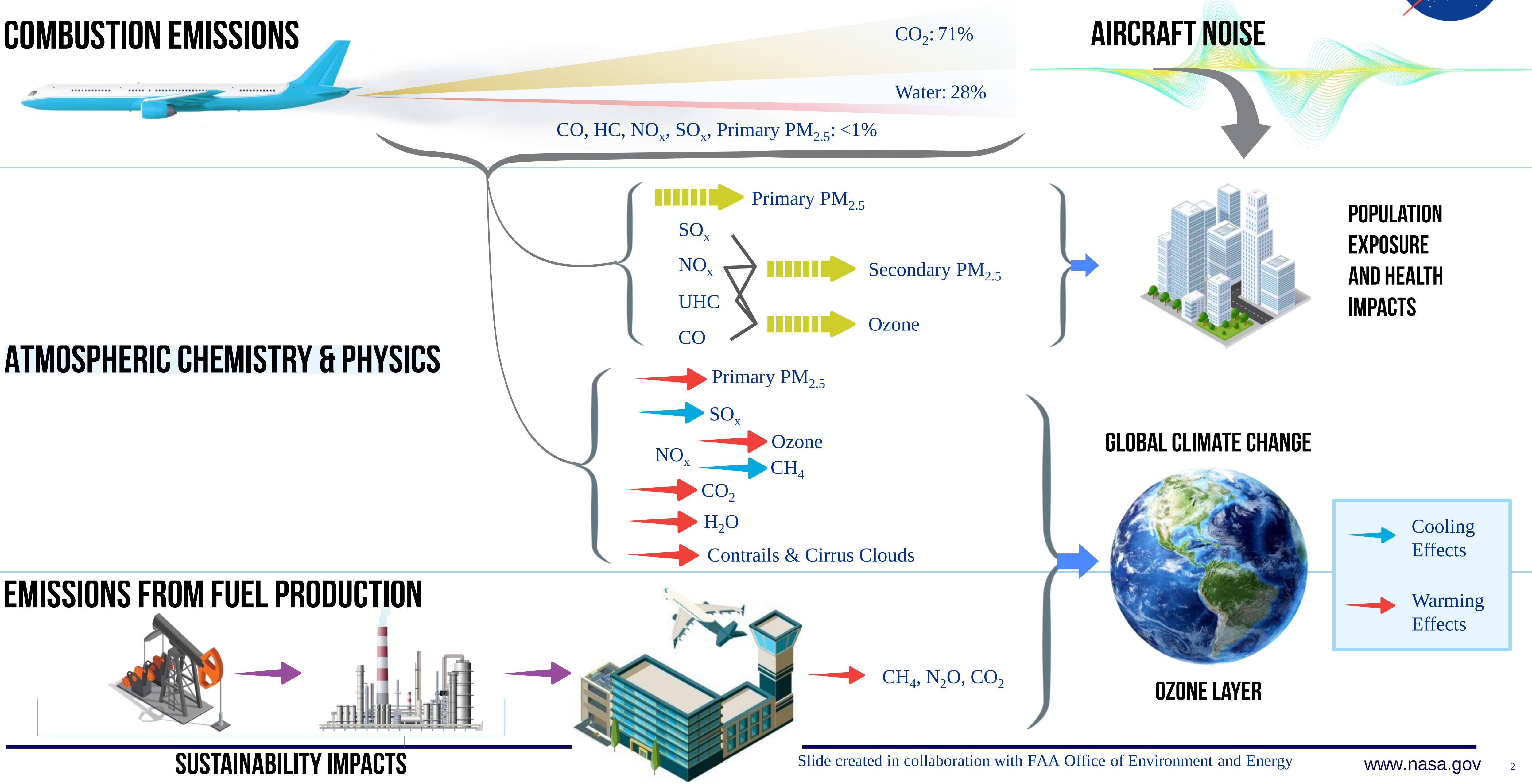
Environmental Impacts of Aviation



COMBUSTION EMISSIONS

CO_2: 71%

Water: 28%

CO, HC, NO_x, SO_x, Primary $PM_{2.5}$: <1%

AIRCRAFT NOISE

ATMOSPHERIC CHEMISTRY & PHYSICS

Primary $PM_{2.5}$

SO_x

NO_x

UHC

CO

Secondary $PM_{2.5}$

Ozone

POPULATION EXPOSURE AND HEALTH IMPACTS

Primary $PM_{2.5}$

SO_x

NO_x

Ozone

CH_4

CO_2

H_2O

Contrails & Cirrus Clouds

GLOBAL CLIMATE CHANGE

OZONE LAYER

Cooling Effects

Warming Effects

EMISSIONS FROM FUEL PRODUCTION

CH_4, N_2O, CO_2

SUSTAINABILITY IMPACTS

Slide created in collaboration with FAA Office of Environment and Energy

Sustainable Flight National Partnership (SFNP)

NASA

INDUSTRY

ACADEMIA

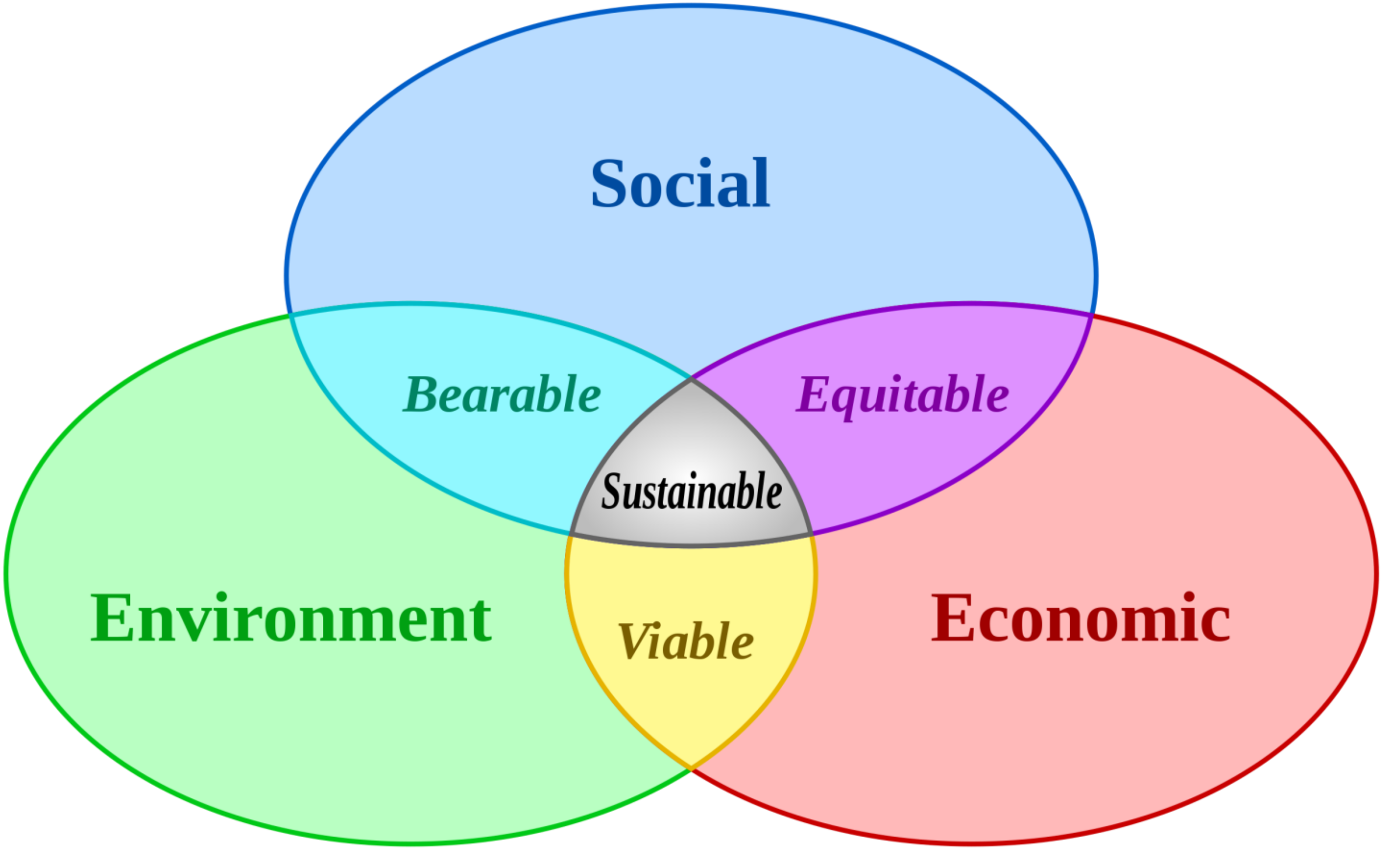
FEDERAL AVIATION ADMINISTRATION

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

USDA

EPA

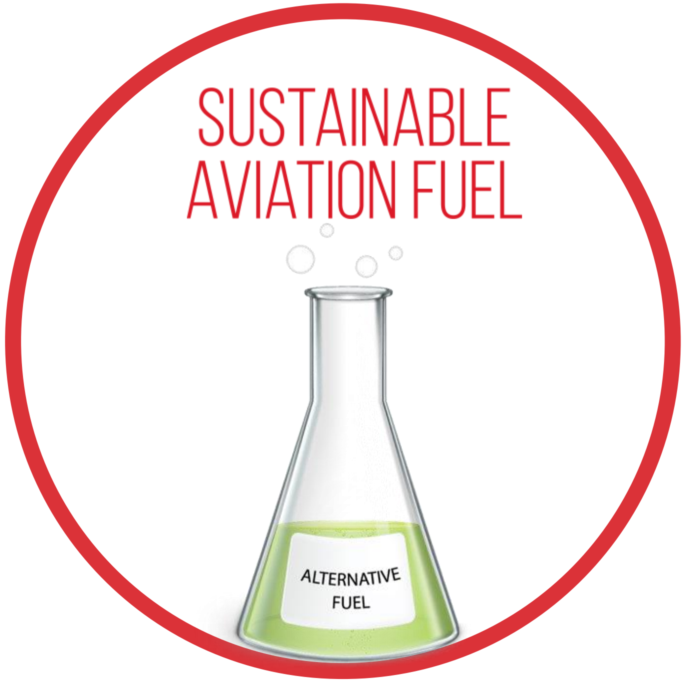


Sustainability is more than aircraft emissions;
it is at the intersection between environmental, social, and economic factors.

Aviation Pillars for a Sustainable Future

TECHNOLOGY

NASA = Primary Role



SUSTAINABLE AVIATION FUEL

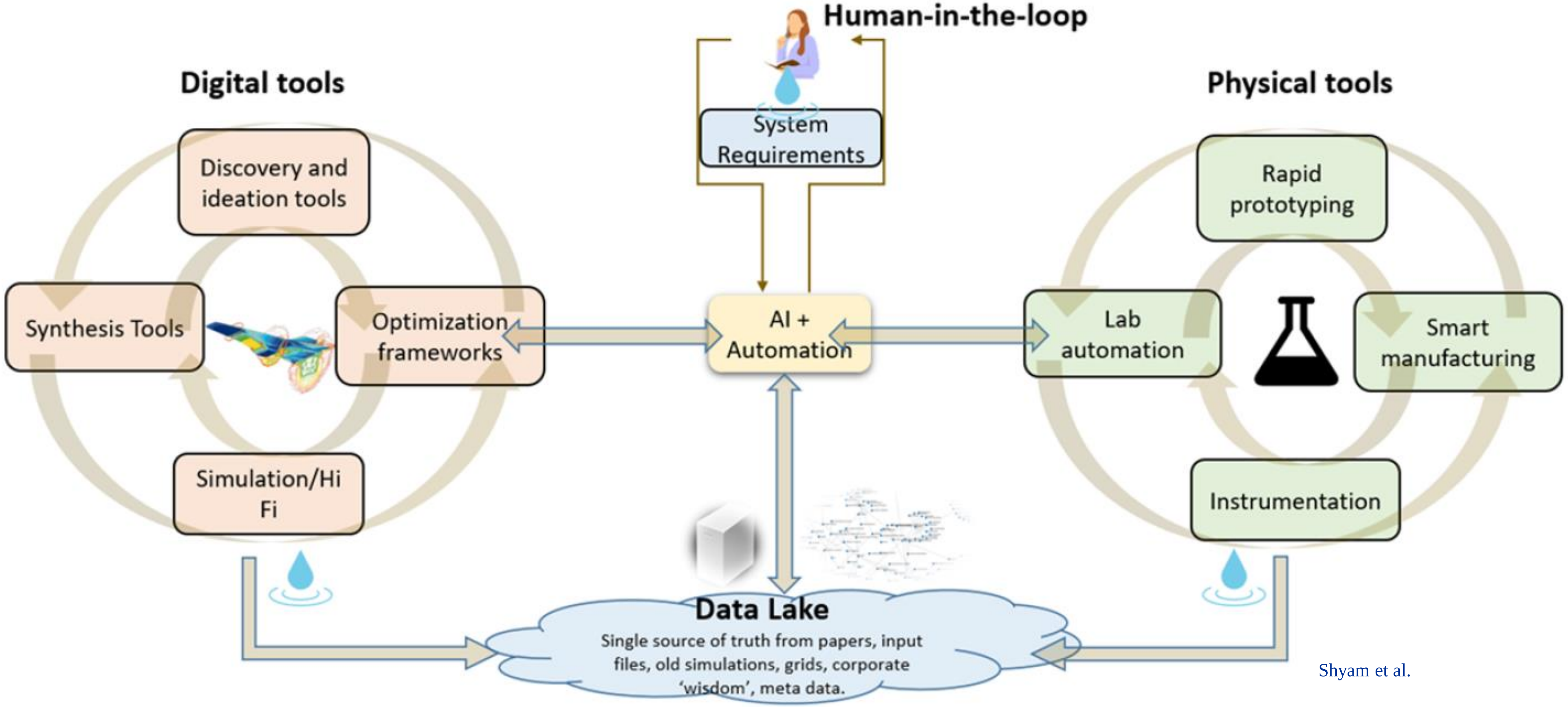
NASA = Supporting Role

OPERATIONS AND INFRASTRUCTURE

NASA = Primary Role

Achieve net-zero greenhouse emissions by 2050 through 25-30% energy efficiency improvements in next-generation transports, 100% sustainable aviation fuel, and optimal trajectories

IDEAS – Intelligent Design and Engineering of Aerospace Systems



Human-in-the-loop

System Requirements

Digital tools

Discovery and ideation tools

Synthesis Tools

Optimization frameworks

Simulation/Hi Fi

AI + Automation

Physical tools

Rapid prototyping

Lab automation

Smart manufacturing

Instrumentation

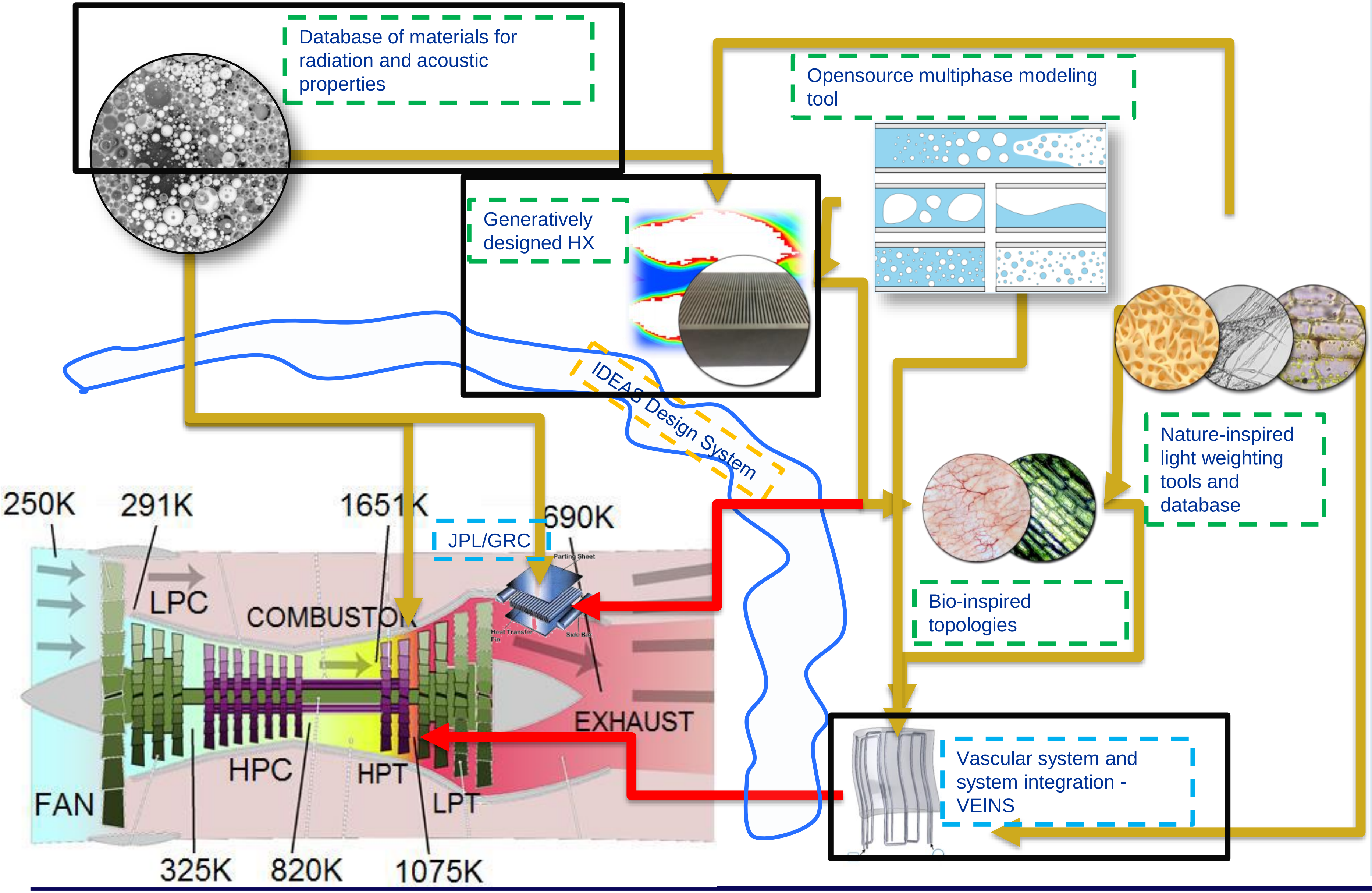
Data Lake

Single source of truth from papers, input files, old simulations, grids, corporate 'wisdom', meta data.

Shyam et al.

Vikram Shyam, Paht Juangphanich, Ezra O. McNichols, Brooke Weborg, Herbert Schilling, Calvin Robinson, Kenji Miki, Manan A. Vyas, Arman Mirhashemi, Joshua Stuckner, Laura Evans, Samaun Nili and Ajay Misra. "IDEAS (Intelligent Design and Engineering of Aerospace Systems)," AIAA 2022-1043. AIAA SCITECH 2022 Forum. January 2022.

Technology Development & Integration



Database of materials for radiation and acoustic properties

Opensource multiphase modeling tool

Generatively designed HX

IDEAS Design System

Nature-inspired light weighting tools and database

Bio-inspired topologies

JPL/GRC

Vascular system and system integration - VEINS

Problem: Develop a heat exchanger for waste heat recovery that allows more than 150kW of heat to be extracted from the gas turbine engine core’s exhaust nozzle with the overall objective to use waste heat in a productive manner.

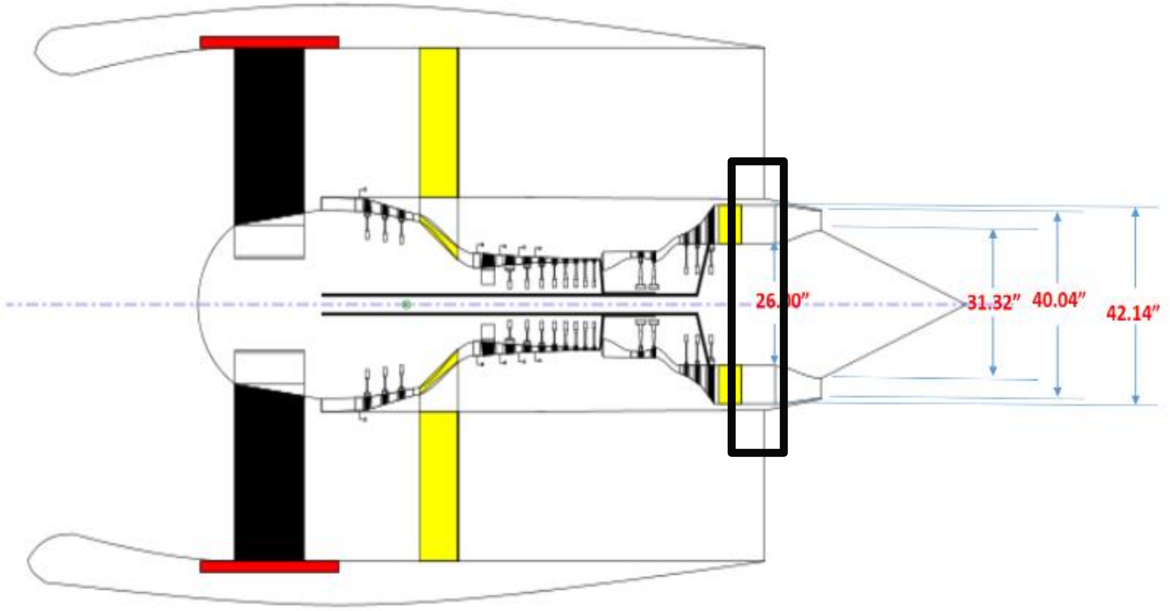
Shyam et al.

Vikram Shyam, Paht Juangphanich, Ezra O. McNichols, Brooke Weborg, Herbert Schilling, Calvin Robinson, Kenji Miki, Manan A. Vyas, Arman Mirhashemi, Joshua Stuckner, Laura Evans, Samaun Nili and Ajay Misra. "IDEAS (Intelligent Design and Engineering of Aerospace Systems)," AIAA 2022-1043. AIAA SCITECH 2022 Forum. January 2022.

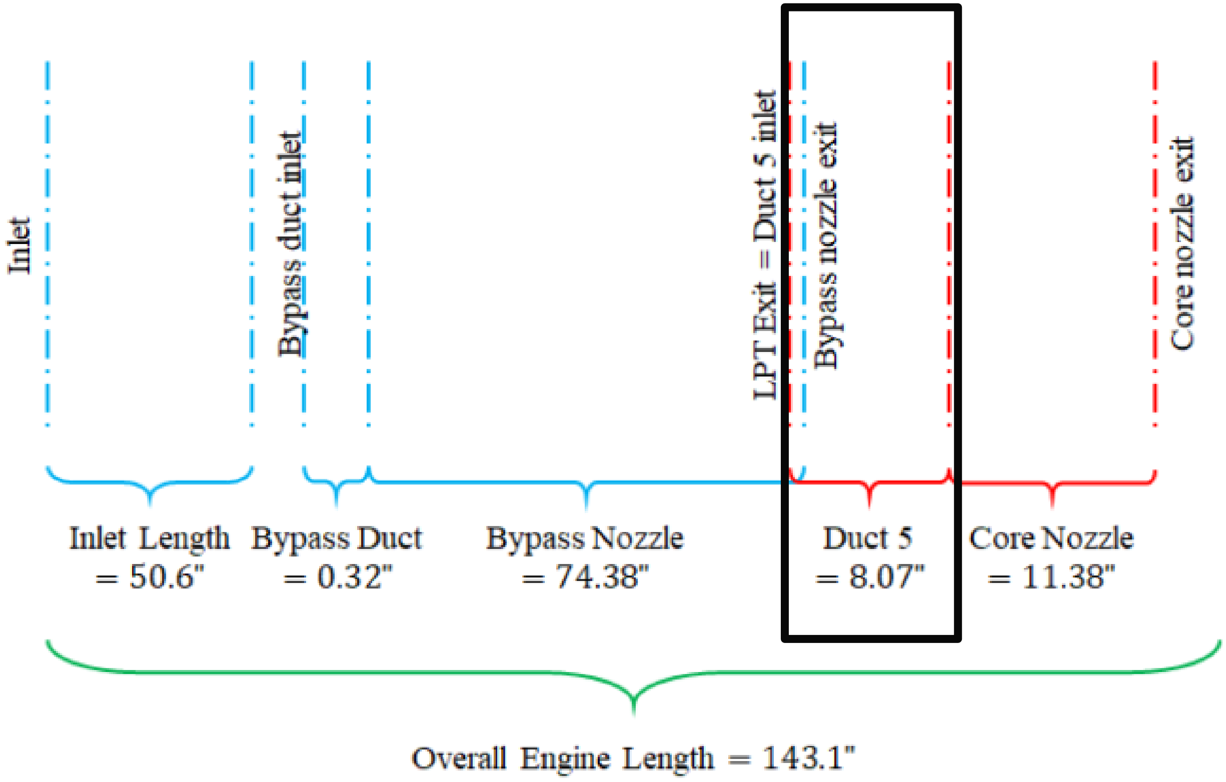
Generatively Designed Heat Exchanger

Project Summary

- Design Heat Exchanger (HX) array to fit in N+3 Small Gear Drive Engine developed by NASA for small core research. HX is used to extract waste heat via thermal acoustic tubes and turned into useful energy.
- Boundary Conditions are provided by simulation of an NPSS model.
- The baseline design is a collaboration with the Electrified Aircraft Propulsion (EAP) subproject and the NASA Jet Propulsion Laboratory (JPL)



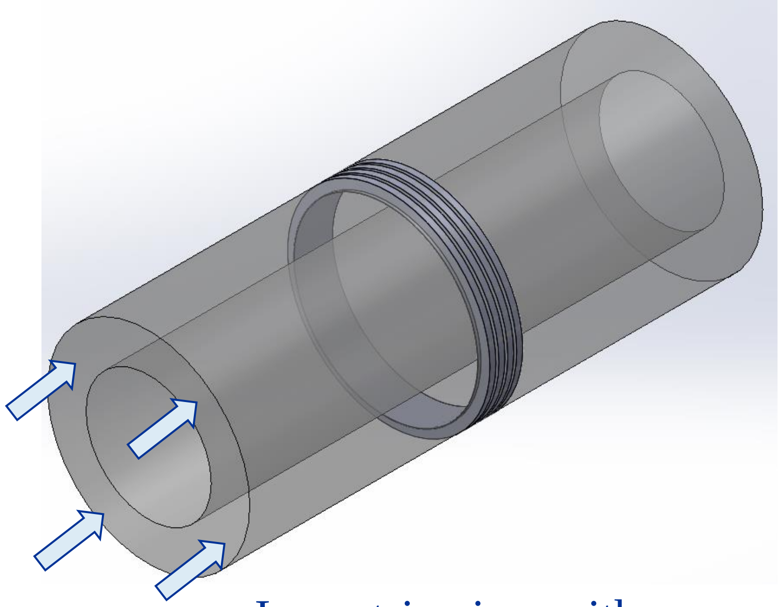
Scott M. Jones, William J. Haller, and Michael T. Tong, An N+3 Technology Level Reference Propulsion System NASA/TM—2017-219501, Glenn Research Center, Cleveland, Ohio



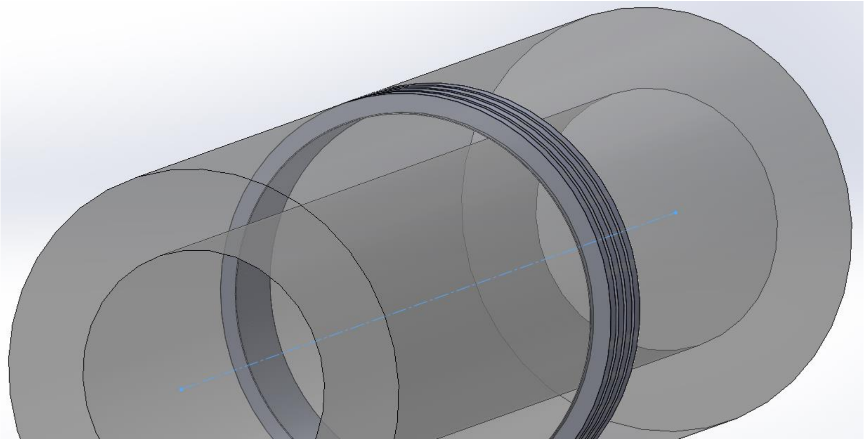
Schematic provided by: Arman.Mirhashemi@nasa.gov

Baseline Design

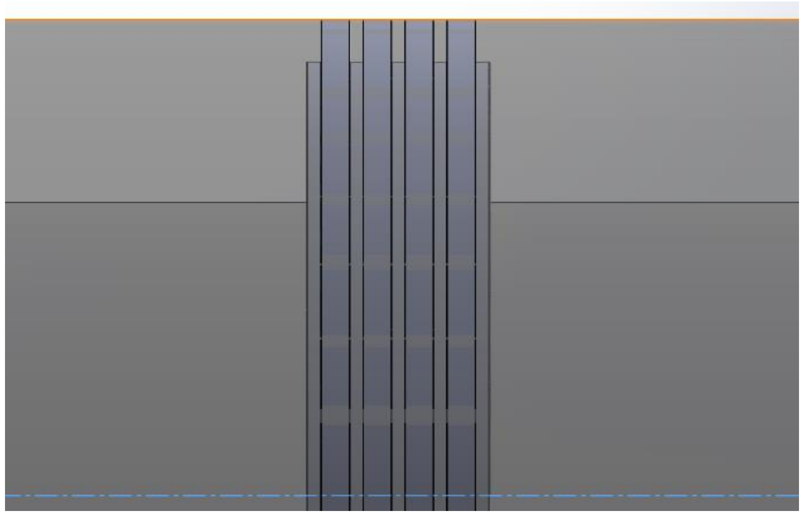
- Heat Exchanger (HX) placement should be in Duct 5 in the core to maximize heat extraction. Previous studies show <5% total pressure loss within the core has minimum effect on performance.
- The radial penetration depth of the HX should not exceed 5 cm to prevent increasing Mach Number due to choking.
- Optimal design: Series of 1.25” tubular HXs separated from the core flow by an inner annulus surface.



Isometric view with inflow arrow



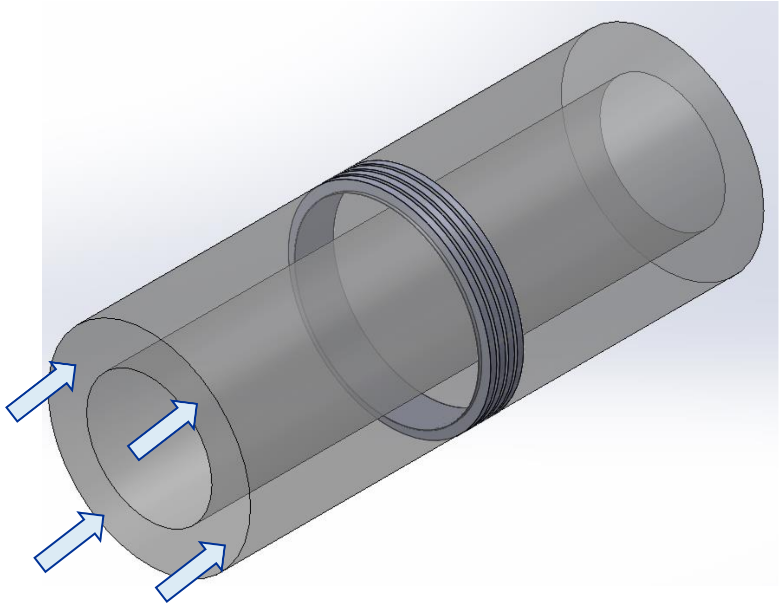
Isometric close-up

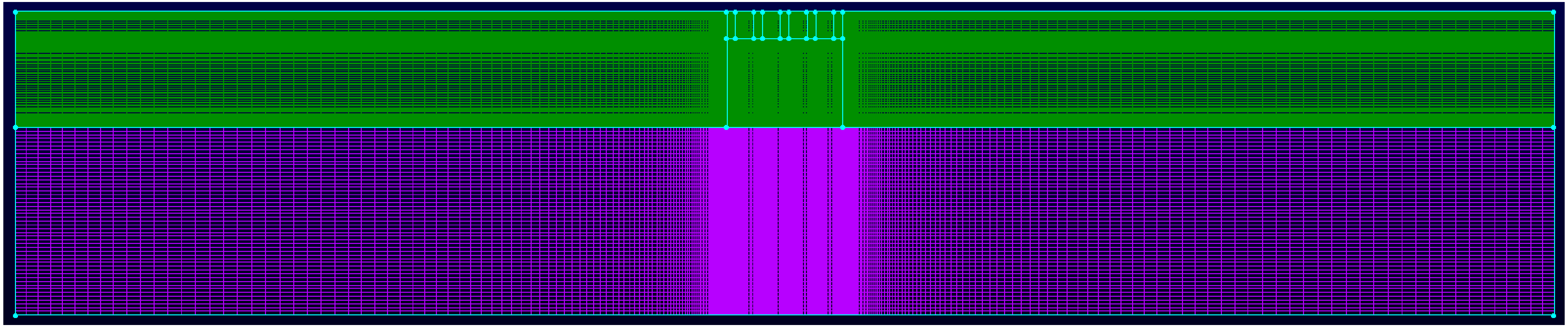


Side view above the axis of rotation

Analysis

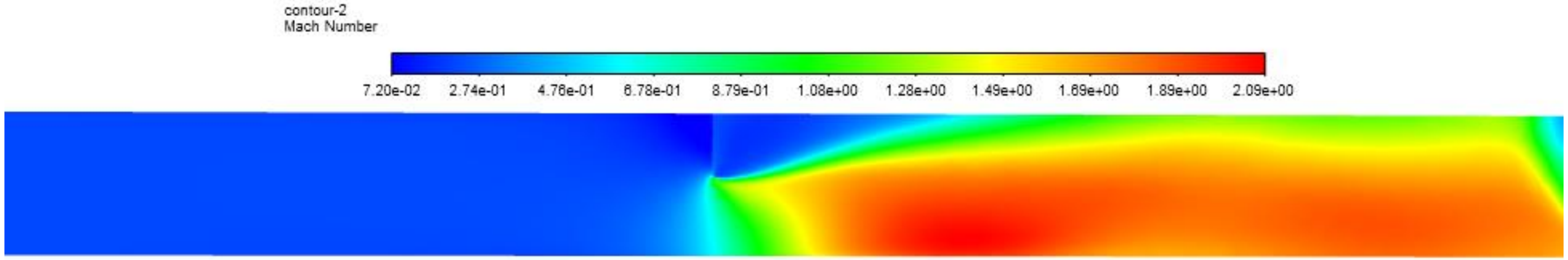
- Simulations using ANSYS Fluent are being performed in 2D and assume axially symmetric results
- Mesh is produced in Pointwise
- (4) Fin Arrays, 1.25” Long, 4.75 cm radial penetration
  - Depth was determined based on impact on Mach number
  - Mach was limited to 0.6 to avoid choking in the core nozzle



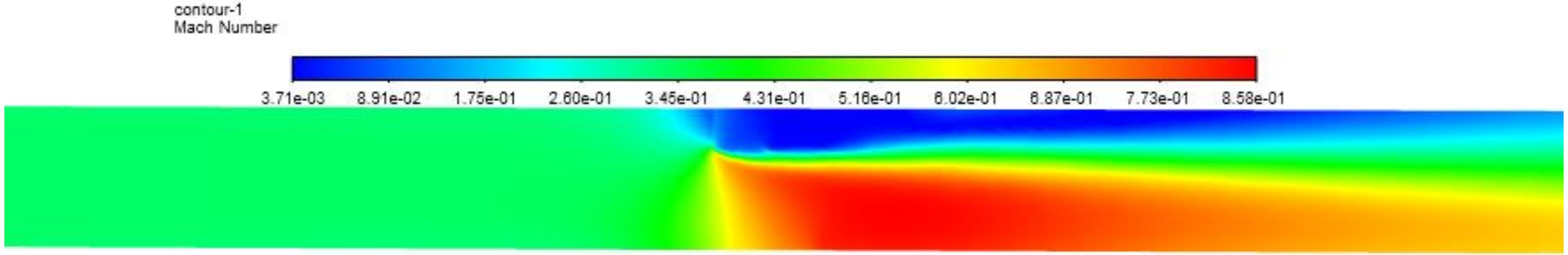


Comparison of Annulus Configuration on Mach Number

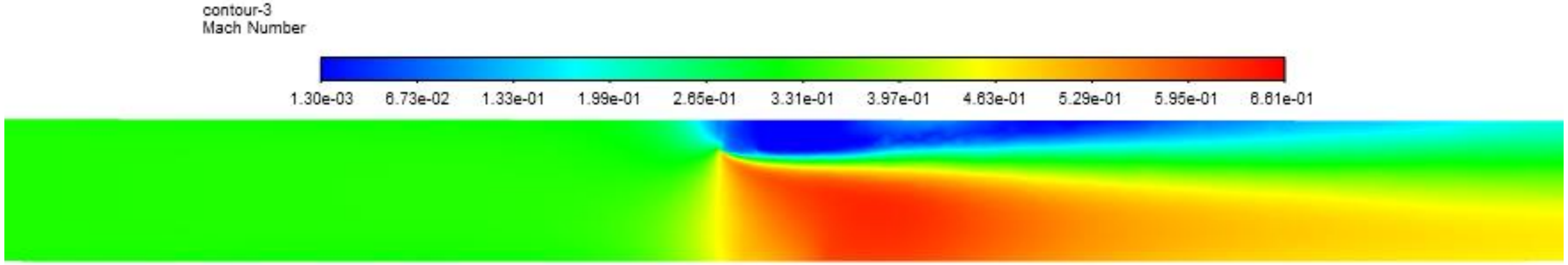
Mach Number cap set at 0.6



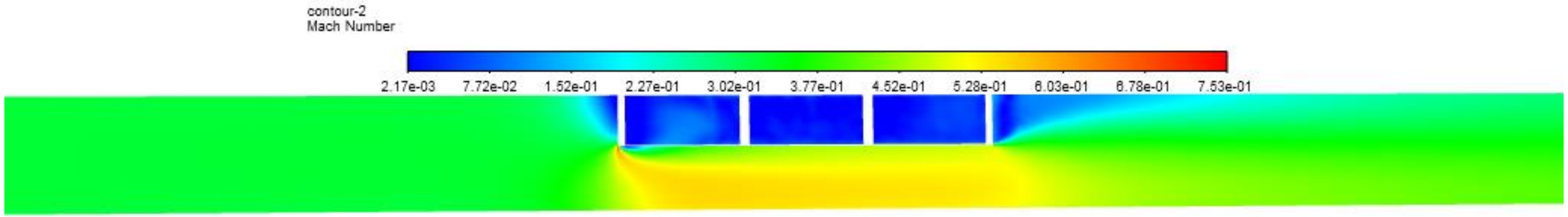
Radial HX Depth = 0.088 m
Avg Core Exit Mach = 1.63



Radial HX Depth = 0.057 m
Avg Core Exit Mach = 0.73



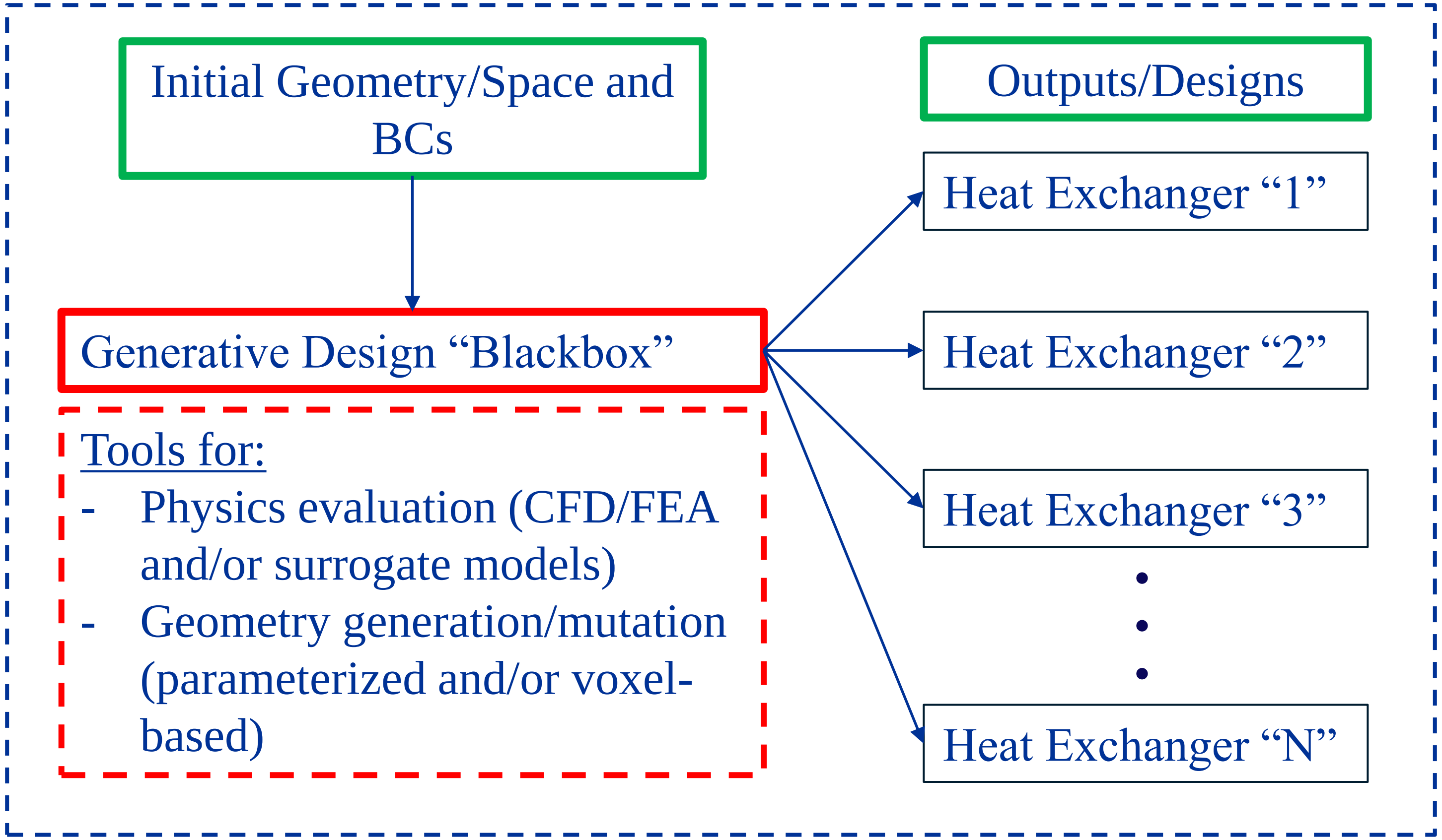
Radial HX Depth = 0.042 m
Avg Core Exit Mach = 0.54



Original Array
Radial HX Depth = 0.084 m
Channel Depth = 0.042 m
Avg Core Exit Mach = 0.52

Generative Design Approach

Replace the fin shapes used in the previous study with shapes formulated through generative design



Initial Geometry/Space and BCs

Outputs/Designs

Generative Design "Blackbox"

Heat Exchanger "1"

Heat Exchanger "2"

Heat Exchanger "3"

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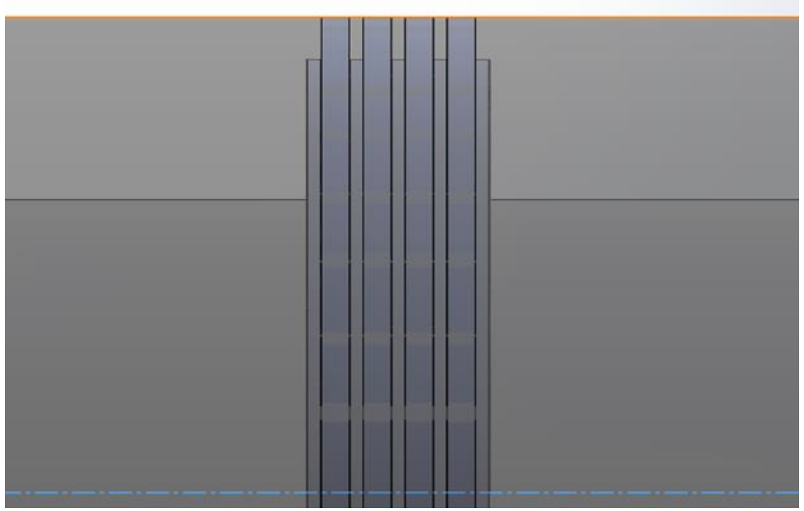
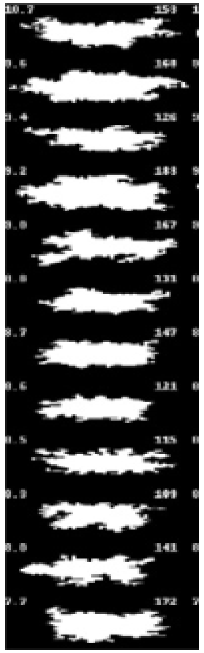
Heat Exchanger "N"

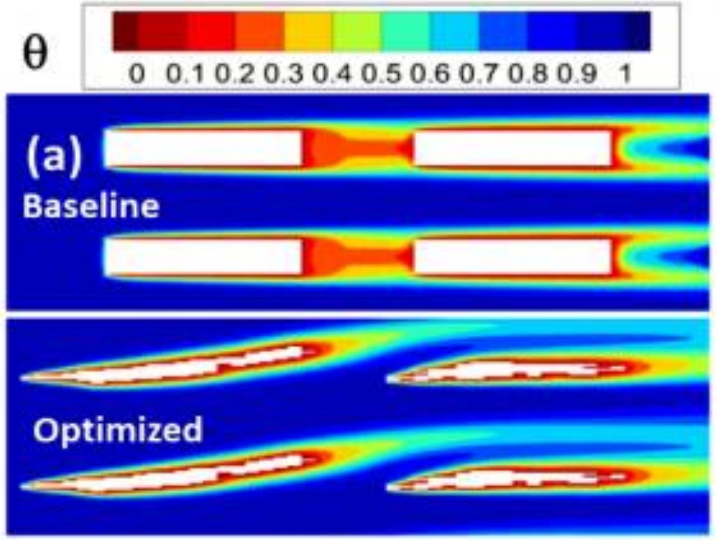
Tools for:

- Physics evaluation (CFD/FEA and/or surrogate models)
- Geometry generation/mutation (parameterized and/or voxel-based)





Mekki et al.



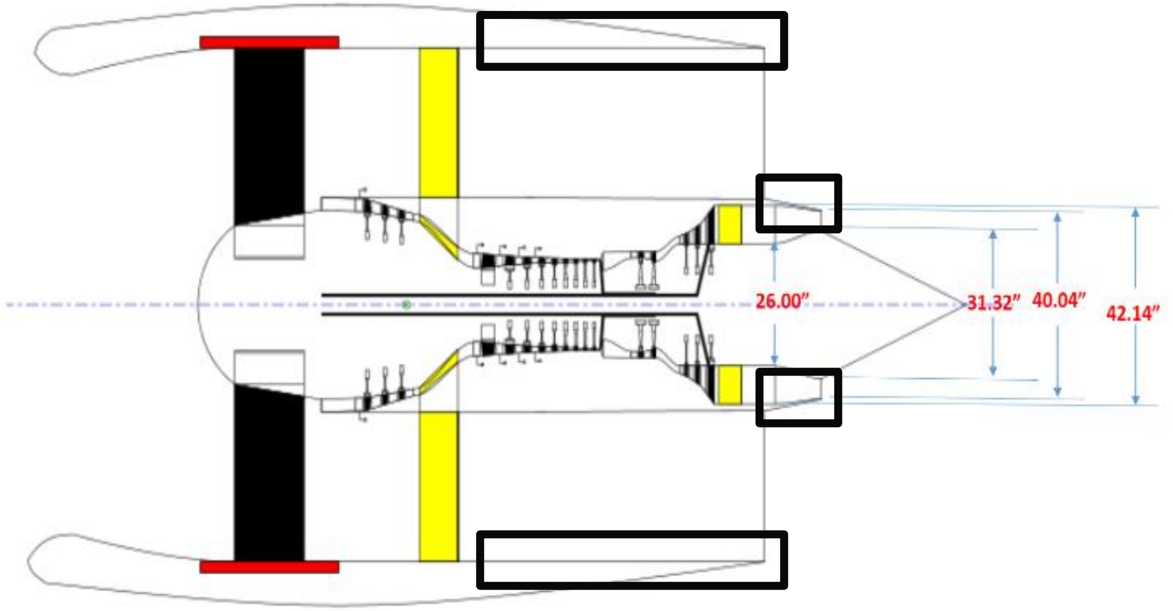
Mekki et al.

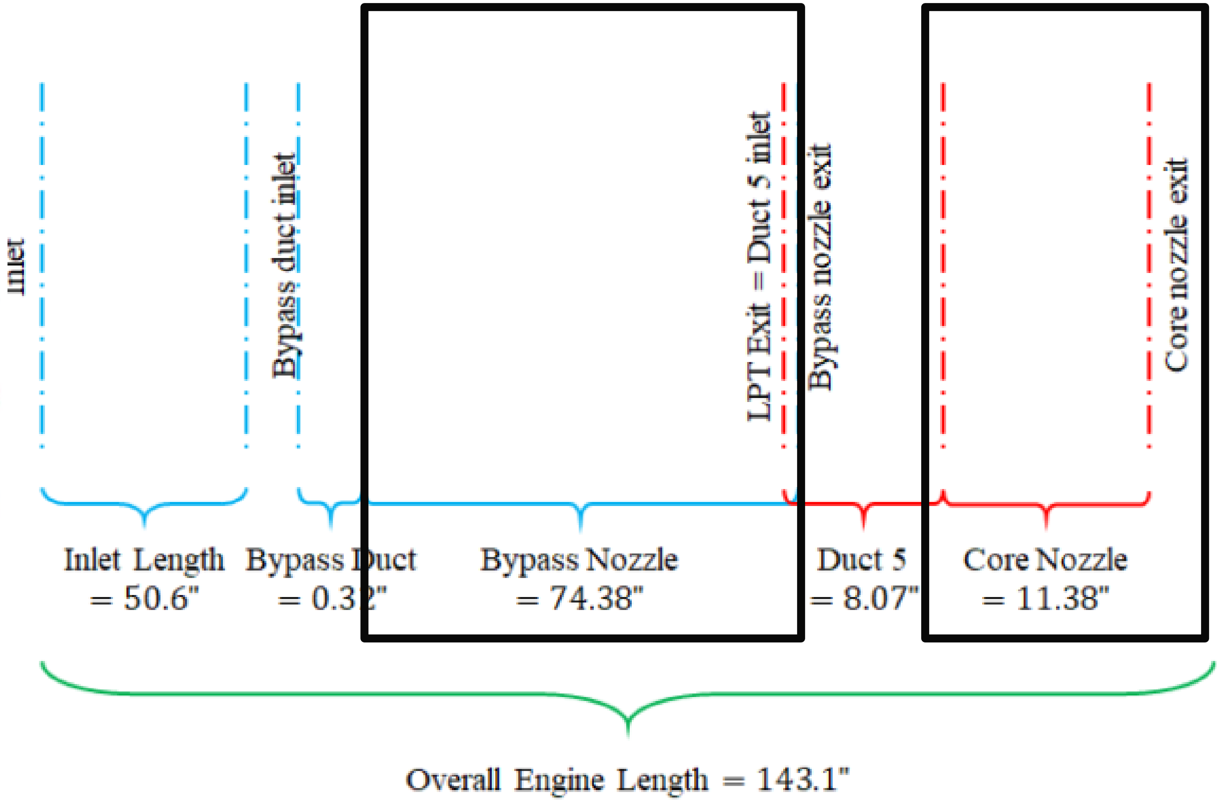
Bashir S. Mekki, Joshua Langer, Stephen Lynch, "Genetic algorithm based topology optimization of heat exchanger fins used in aerospace applications", International Journal of Heat and Mass Transfer, Volume 170, 2021, 121002, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2021.121002.

Multifunctional Acoustic/Thermal Liner

Project Summary

- Design Multifunctional Liner that can act as both an absorber for both acoustics and thermal radiation
    - Mitigate noise, while being able to harvest waste heat from core exhaust nozzle
- Acoustics needs to mitigate the frequency range of interest
- Radiative surface absorption spectra needs to match the emission spectra of the hot gas





Scott M. Jones, William J. Haller, and Michael T. Tong, An N+3 Technology Level Reference Propulsion System NASA/TM—2017-219501, Glenn Research Center, Cleveland, Ohio

Schematic provided by: Arman.Mirhashemi@nasa.gov

Multifunctional Liner

- Granular materials to design and fabrication of a porous material by controlling the pore size and their distribution by selecting appropriate granular sizes.
- Lightweight granular ceramic hollow microbubbles are one of the best choices.

NC A&T Acoustic Test
Sample Diameter, D = 100mm
Sample Thickness, t =1” or 25 mm
Frequency Range: 250 – 1600 Hz
Results: 1. Extendospheres(Ø$_d$ = 450 µm)

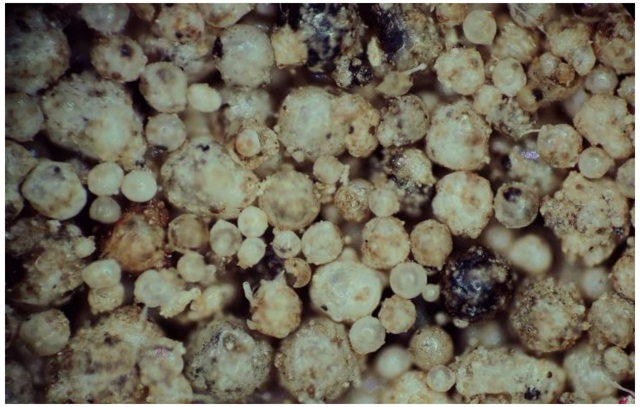
α – 0.10 to 0.75
TLn – 11 to 13 dB

2. Extendospheres(Ø$_d$ = 160 µm)

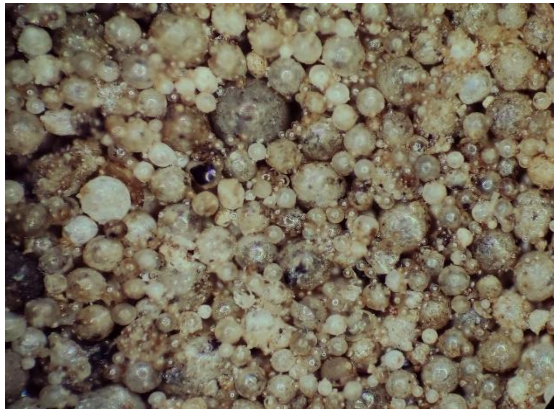
α – 0.16 to 0.35
TLn – 14 to 23 dB

3. Cenospheres(Ø$_d$ = 70 µm)

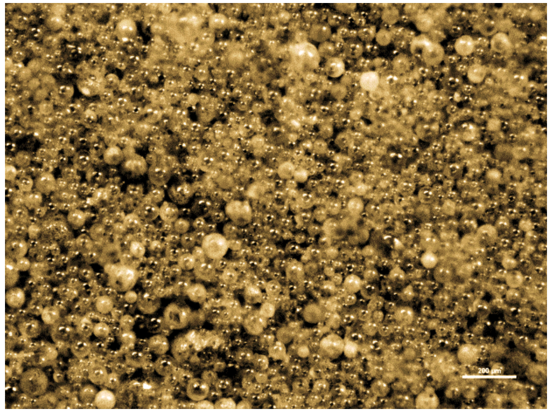
α – 0.10 to 0.30
TLn – 18 to 26 dB



Extendospheres (150 - 850µm) Ø$_d$ = 450 µm



Extendospheres (10 - 500µm) Ø$_d$ = 160 µm

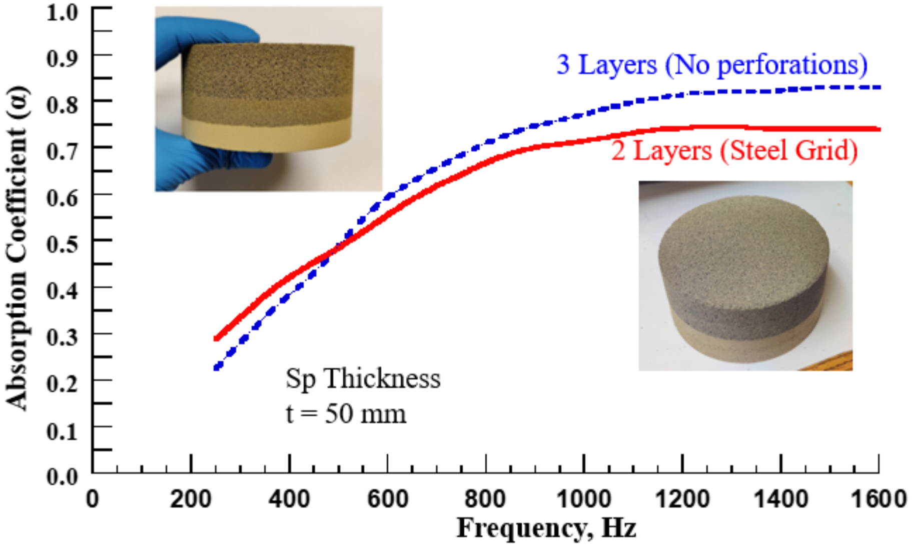


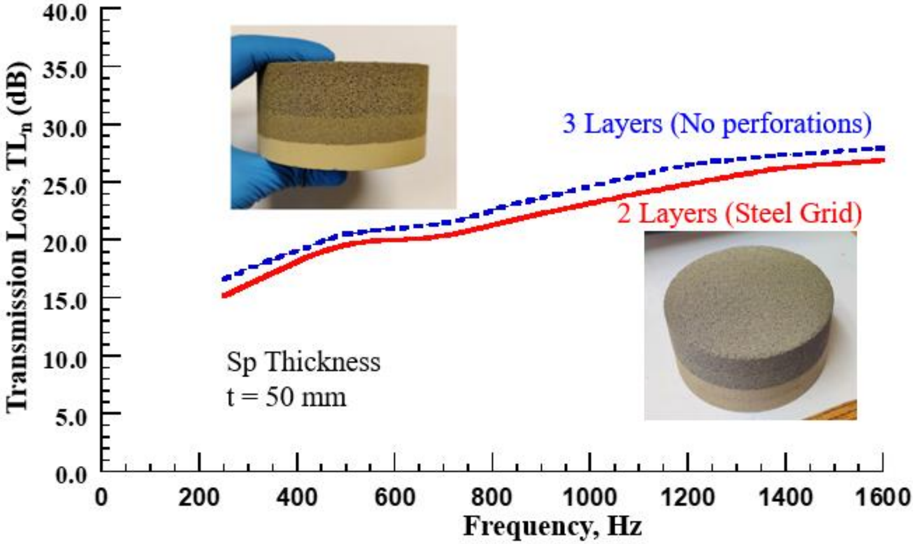
Cenospheres (10 - 100 µm) Ø$_d$ = 70 µm

UC Irvine to Perform

- Optical and thermal properties
- UV-Vis-NIR spectroscopy
- FTIR, and IR thermography

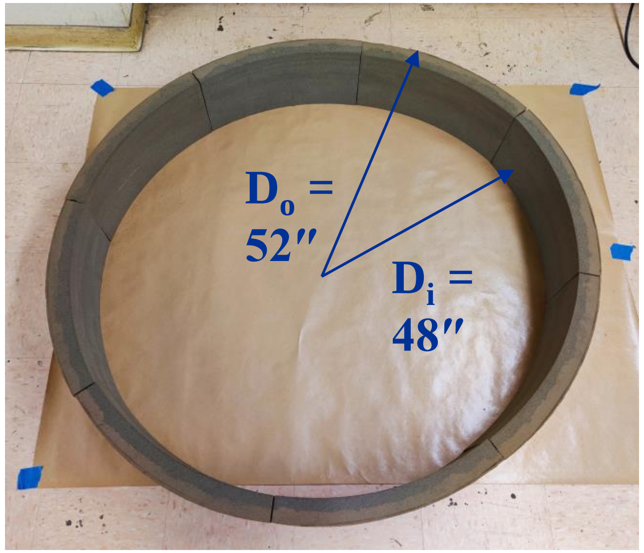
Multifunctional Liner – Acoustics TRL Advancement

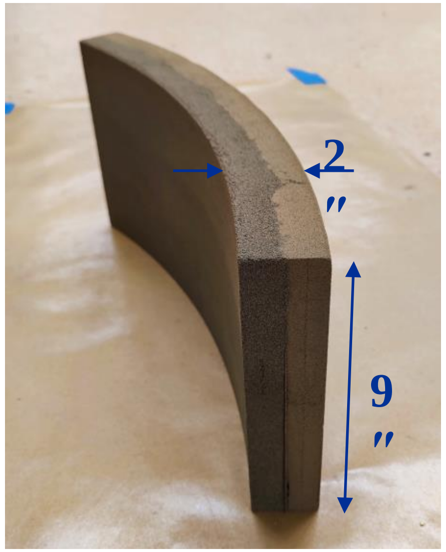




Low TRL Testing

Normal Incidence Impedance Test – North Carolina A&T



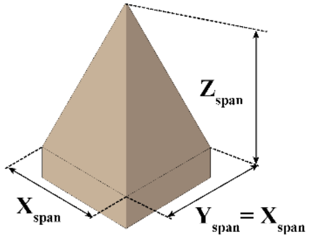


ANCF Test – University of Notre Dame

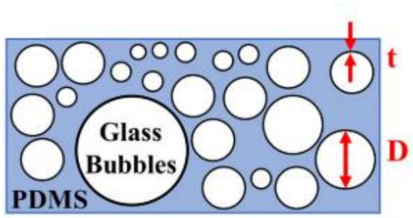
Tunable Radiation with Surface Microstructures

<u>Goal:</u> Use machine learning to analyze and design surface microstructures to change the wavelength of reflection and emission from a surface. This will enable design and fabrication of novel, scalable, reconfigurable, and multifunctional surface coatings for optimal radiative heat transfer.[1,2]

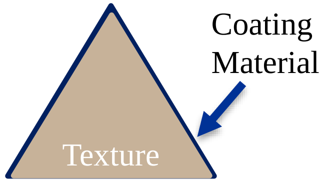
Microstructures



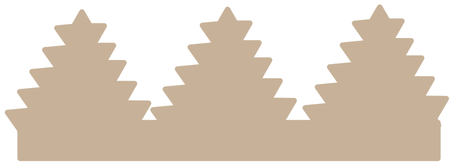
Micropyramids



Microspheres

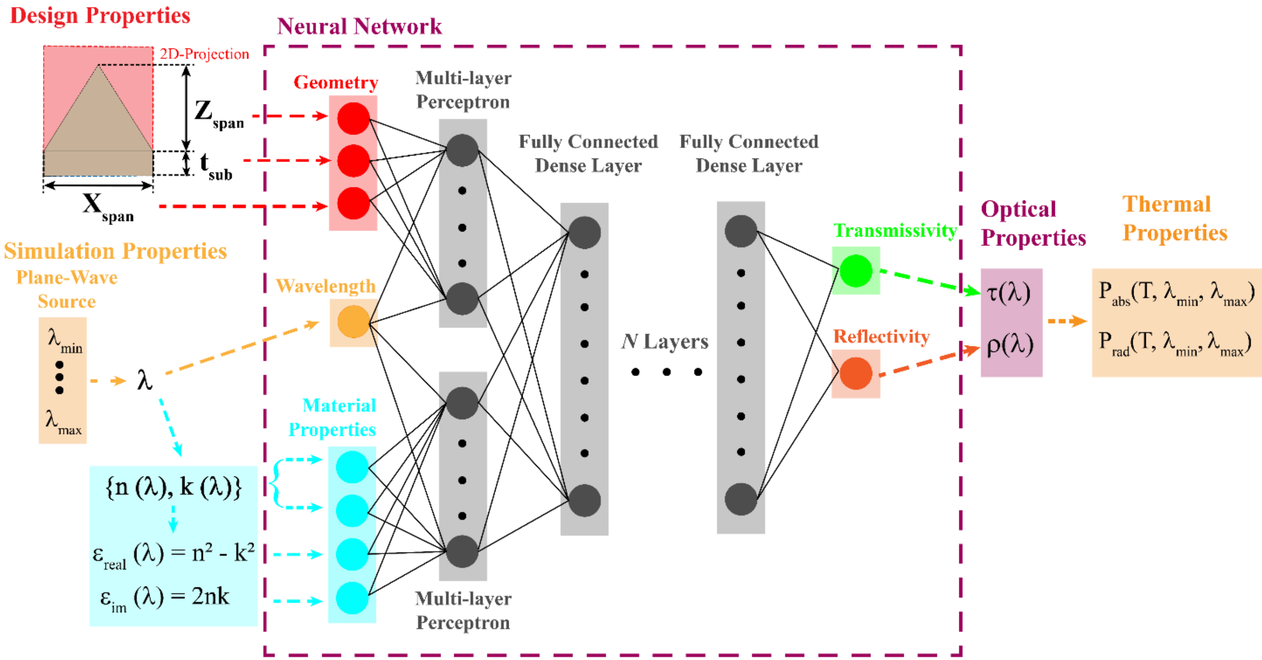


Multilayer/Coated



Hierarchically Textured

Neural Network for Analysis



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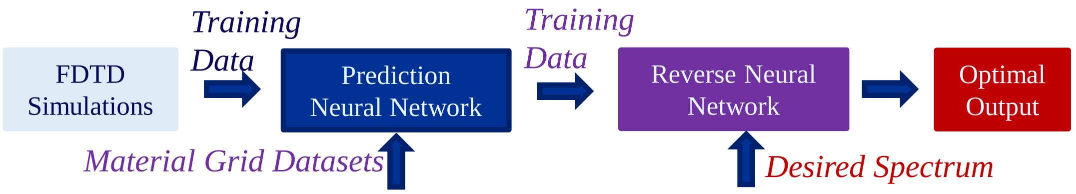
1. Sullivan, J., Yu, Z. and Lee, J., 2021. Optical Analysis and Optimization of Micropyramid Texture for Thermal Radiation Control. *Nanoscale and Microscale Thermophysical Engineering*, *25*(3-4), pp.137-152.
2. Sullivan, J., Mirhashemi, A. and Lee, J., 2022. Deep learning based analysis of microstructured materials for thermal radiation control. *Scientific reports*, *12*(1), pp.1-14.

Tunable Radiation with Surface Microstructures

While the ANN model enables predicting thermal performance of various structures it cannot be directly to design for specific requirements. The design process incorporates a semi-adversarial approach to allow for finding designs and materials which are not solely limited to the training data-sets.[1]

Design Process



Training Data

FDTD Simulations

Prediction Neural Network

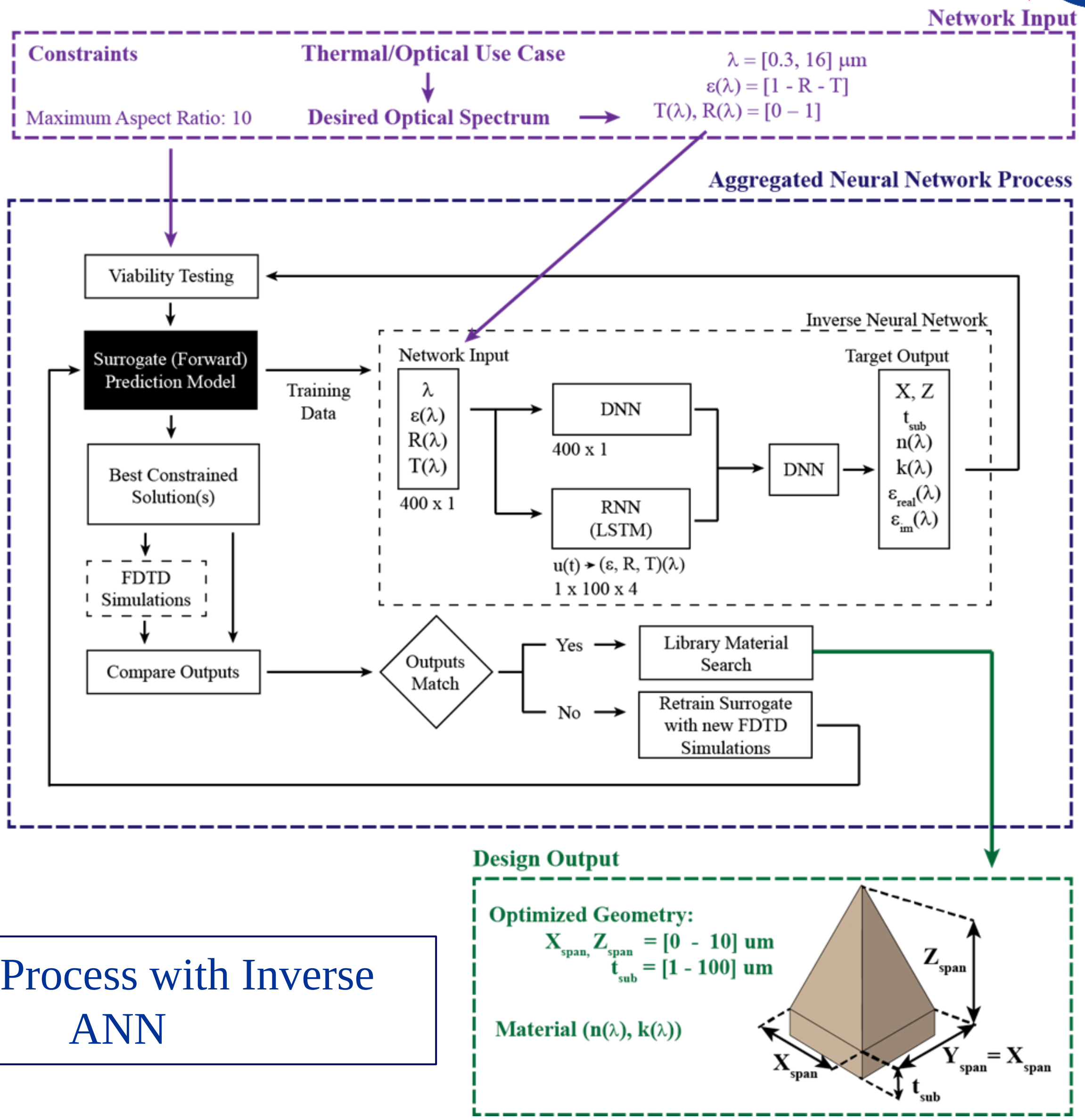
Material Grid Datasets

Training Data

Reverse Neural Network

Desired Spectrum

Optimal Output



Design Process with Inverse ANN

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[1] Under work for publication.

Multifunctional Liner – Acoustics and Thermal

Fully integrated development leading to TRL 4 test in FY24

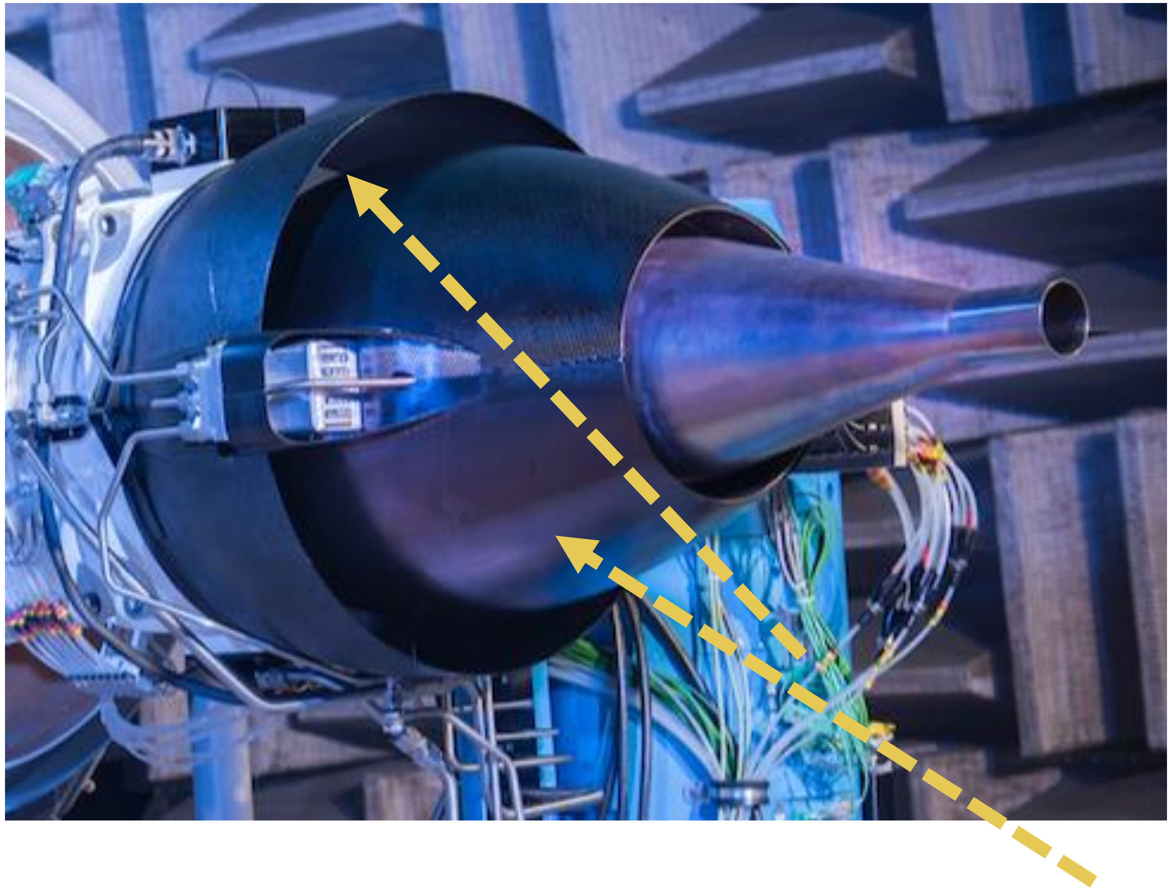
DART (DGEN380 Aero-propulsion Research Turbofan)

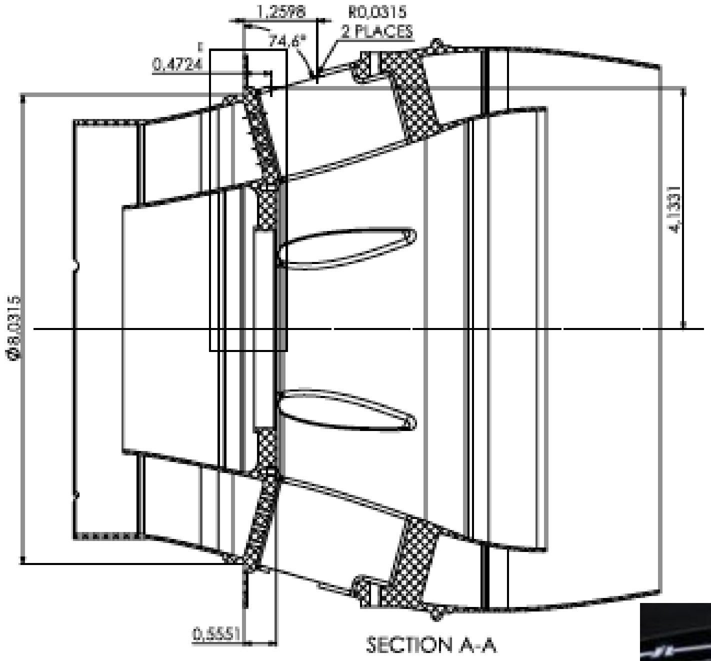
Drawings exist (available for internal use, including internal contactor)
external contactor requires permission
(flow path ‘possibly’ – rotating parts less likely)
Vendor support available

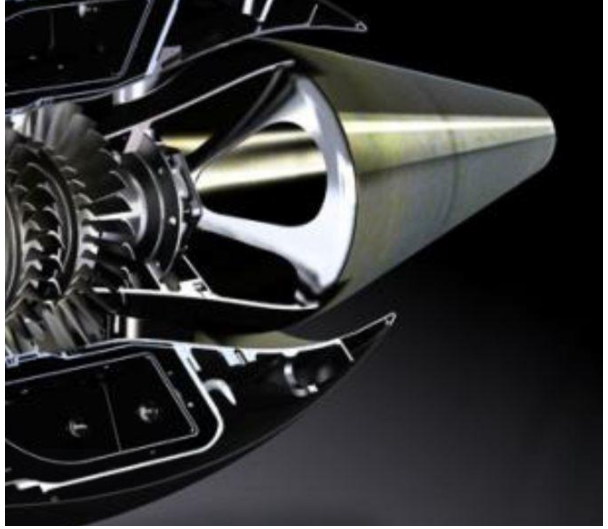
MFL can be installed in the bypass duct nozzle.
The core duct nozzle yields the higher temperature that may be required for thermal evaluation (see next slide)

Multifunctional Liner

DGEN Exhaust Flow Nozzles



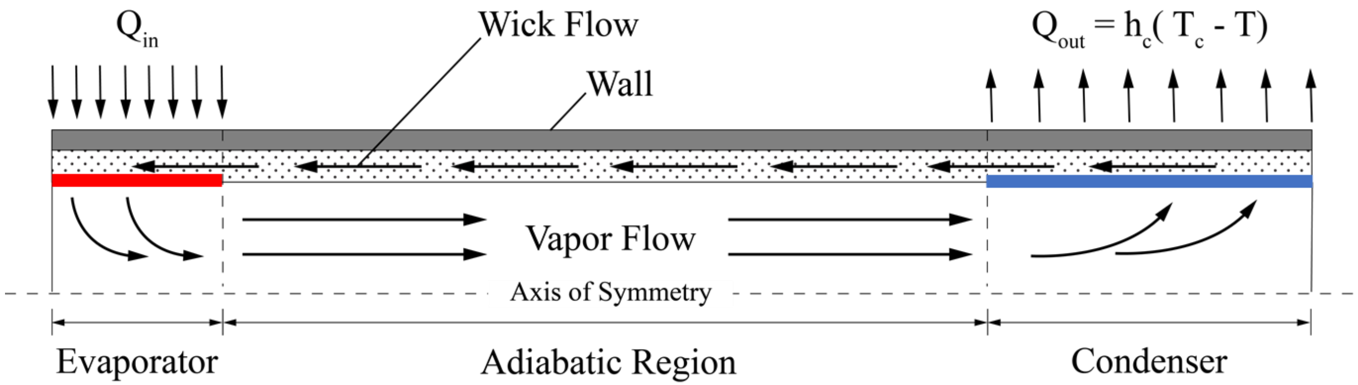


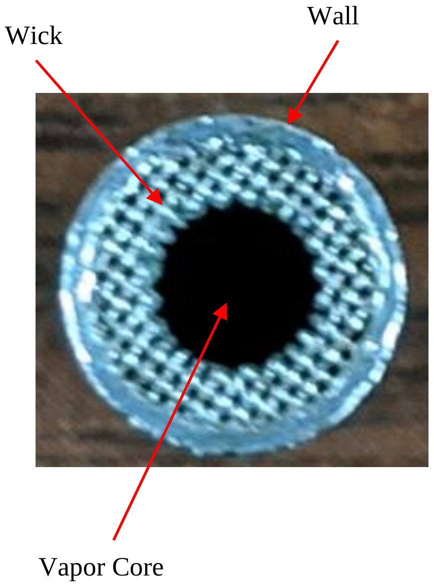


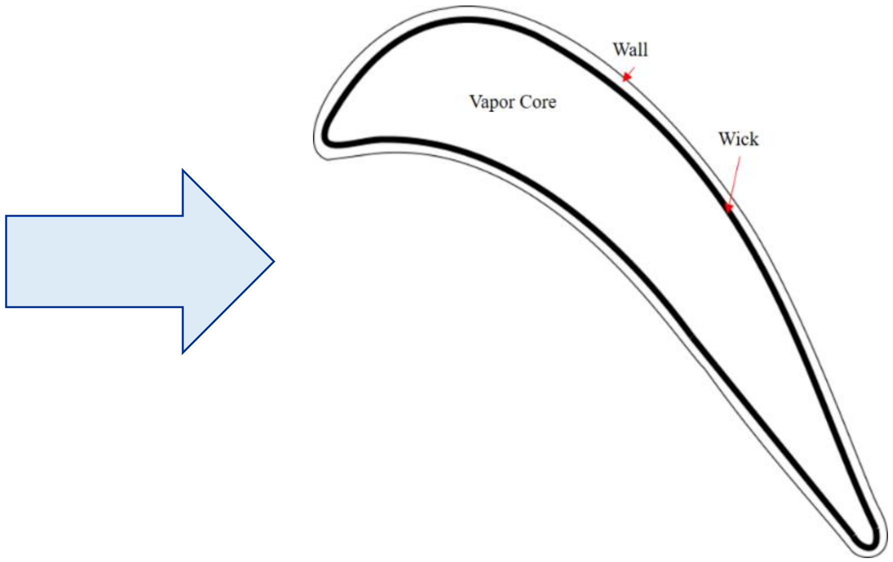
Alternative material surface for thermal radiation will be provided.

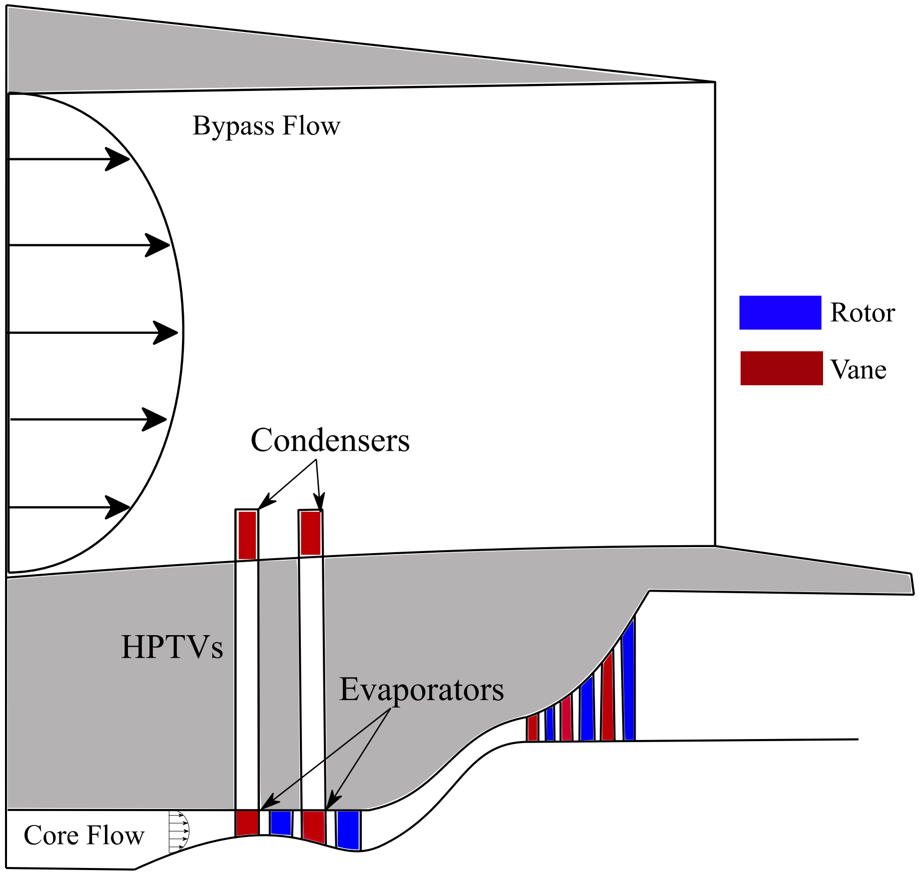
Multifunctional Turbine Vanes

Concept Description



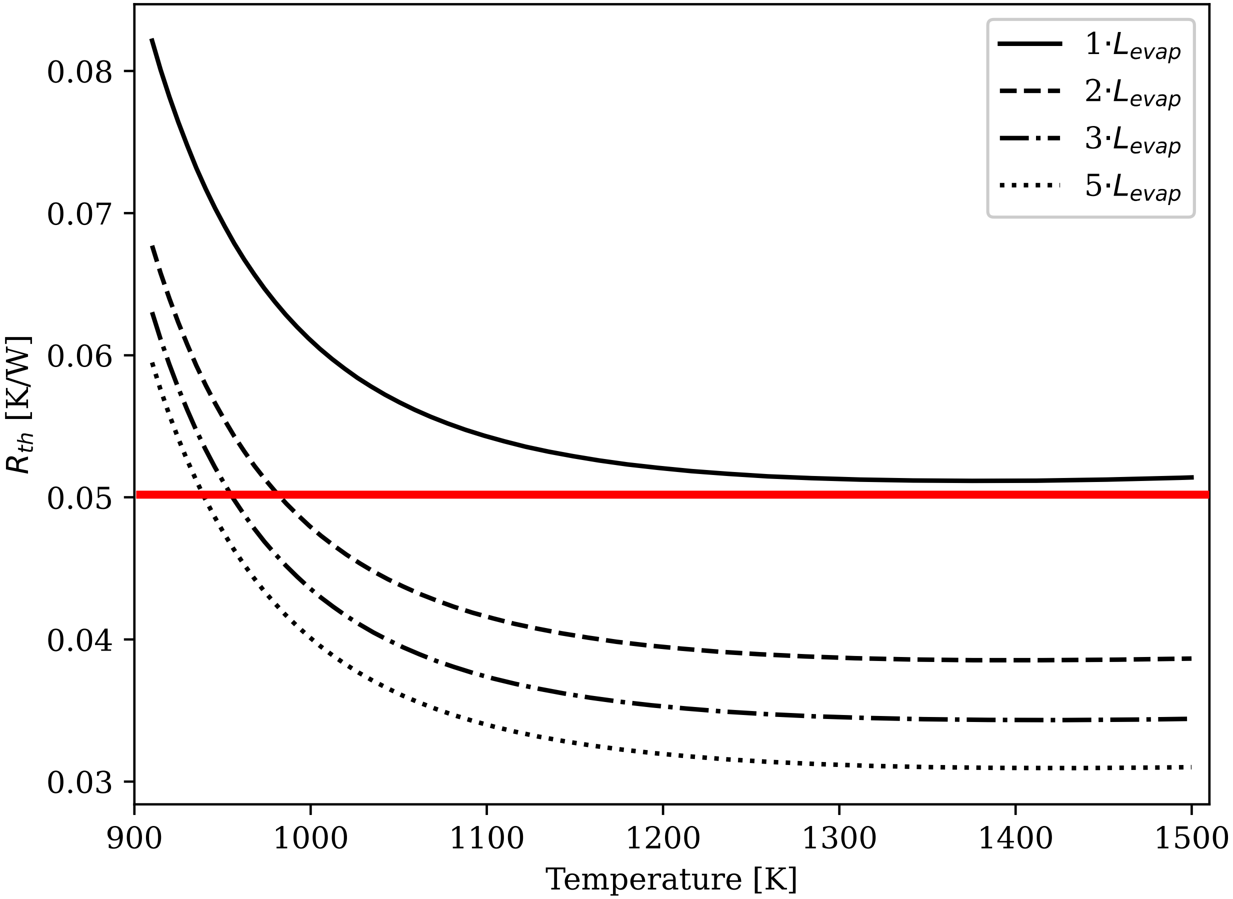






McNichols, E.O., Jones, S.M., Mirhashemi, A., Juangphanich, P., and Shyam, V. (2021). Preliminary Study of Heat Pipe Turbine Vane Cooling in the NASA N+3 Reference Engine, Proceedings of the ASME Turbo Expo, GT2021-59352, 7-11 June 2021.

Thermal Performance



- Condenser length was varied
  - Easiest to change, since AM is most likely the method of manufacturing
- Larger lengths may cause an issue for limitations
  - Operating at too low of a temperature may push operating point toward a limitation

McNichols, E.O., Jones, S.M., Mirhashemi, A., Juangphanich, P., and Shyam, V. (2021). Preliminary Study of Heat Pipe Turbine Vane Cooling in the NASA N+3 Reference Engine, Proceedings of the ASME Turbo Expo, GT2021-59352, 7-11 June 2021.

System-Level Impact

	Baseline	HPTV
Fan Pressure Ratio, FPR	1.30	1.30
Overall Pressure Ratio, OPR	55	55
Bypass Ratio, BPR	23.9	25
Burner Exit Temperature, T4	1750 K	1700 K
HPT Rotor 1 Temperature, T41	1700 K	1700 K
HPT Cooling Flow (% of Core Flow)		
Stage 1 Vanes	6.2%	0.0%
Stage 1 Rotors	3.2%	3.1%
Stage 2 Vanes	3.4%	0.0%
Stage 2 Rotors	1.3%	1.4%
LPT Cooling Flow	0.0%	0.0%
Top-Of-Climb Net Thrust	27.1 kN	26.9 kN
Top-Of-Climb Fuel Flow	0.353 kg/s	0.352 kg/s
Heat Removal from HPT Stage 1	0.00	116.6 kW
Heat Removal from HPT Stage 2	0.00	111.1 kW
Heat Addition to Bypass	0.00	227.7 kW

Key Points:

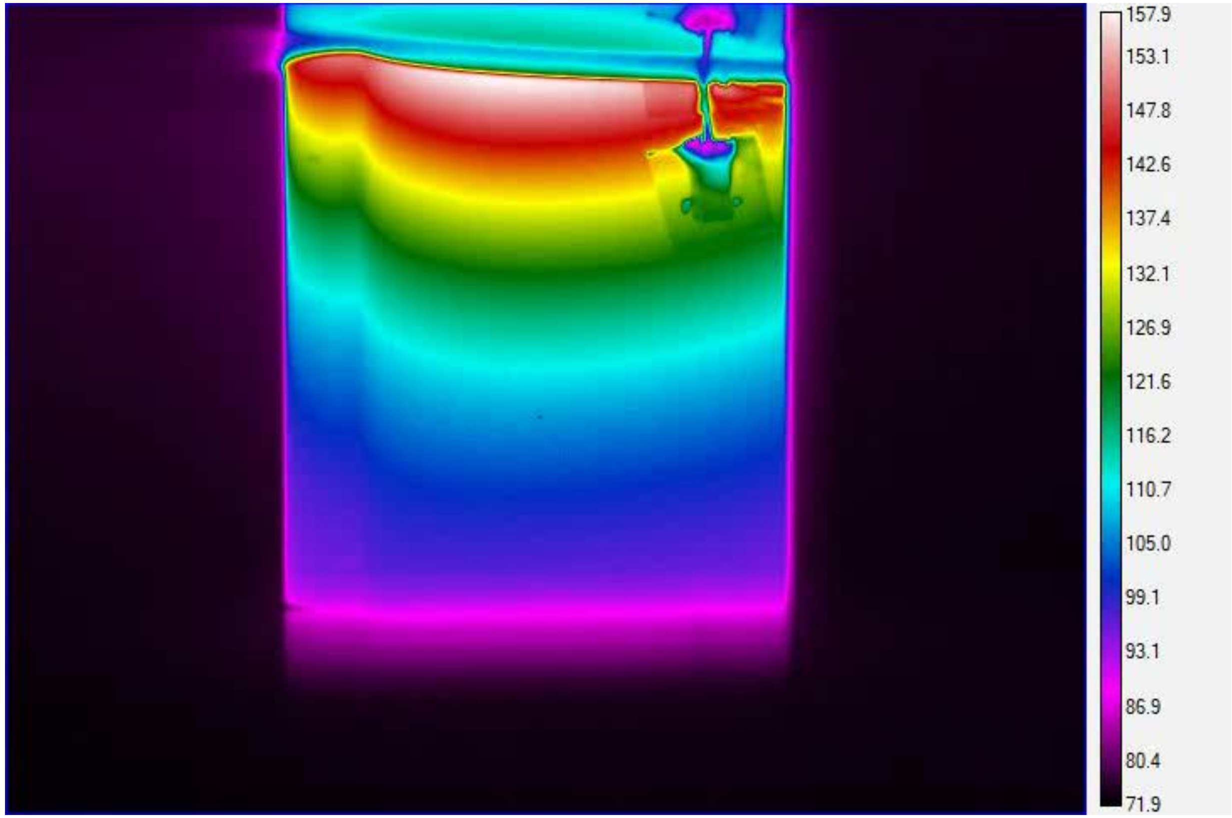
- T41 held constant to keep rotor cooling flows similar
- Sea-level static takeoff thrust was held constant, resulting in minor thrust difference at TOC
- 0.50 % reduction in thrust, and a 0.20 % decrease in fuel flow, combine for a 0.20 % increase in TSFC

Bypass Loss and Stage Efficiency Considerations:

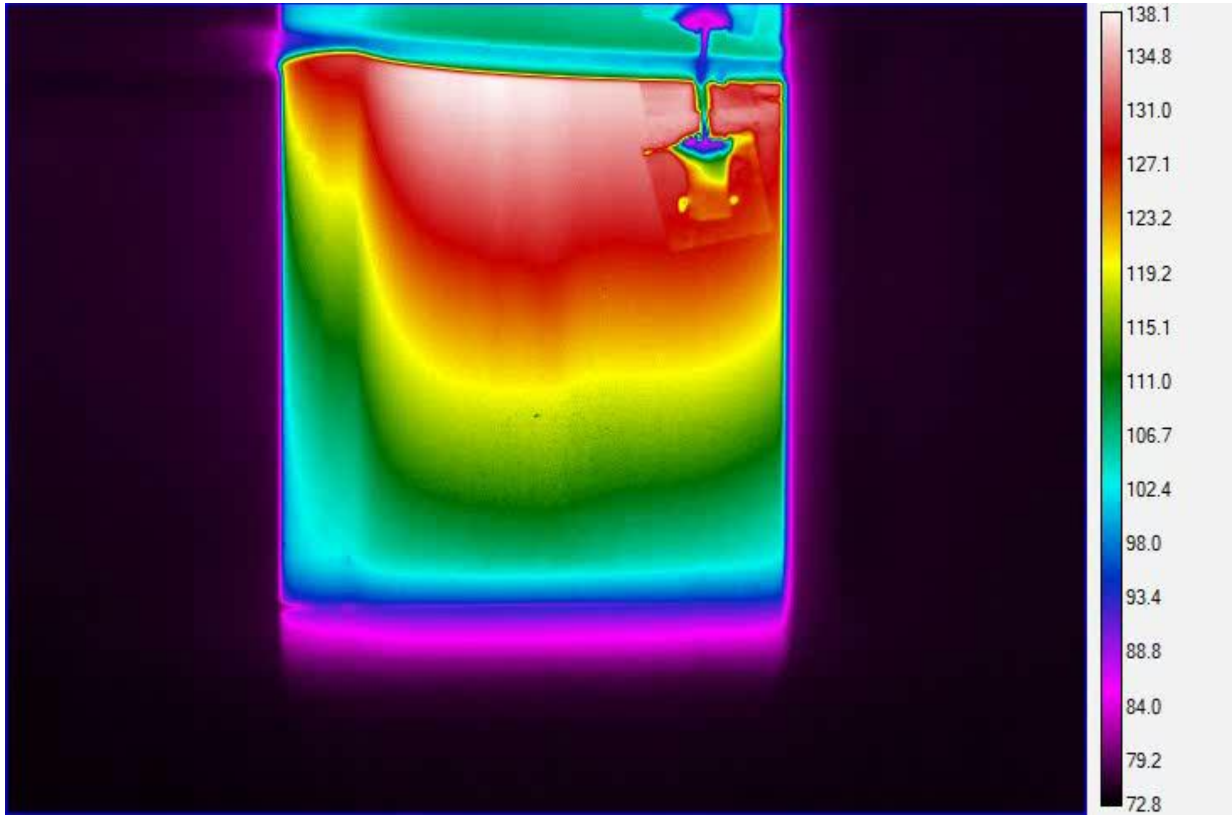
- TSFC decreases by 0.40% for each 1% improvement in HPT stage efficiency
- TSFC increases by 1% for 0.375% pressure loss in the bypass (estimated for this study)
- For this cycle, turbine stage efficiency would need to improve by at least 3% to outweigh bypass penalty

McNichols, E.O., Jones, S.M., Mirhashemi, A., Juangphanich, P., and Shyam, V. (2021). Preliminary Study of Heat Pipe Turbine Vane Cooling in the NASA N+3 Reference Engine, Proceedings of the ASME Turbo Expo, GT2021-59352, 7-11 June 2021.

Oscillating Heat Pipe Turbine Vane



80W Power – Baseline (Empty)



80W Power - Working OHP

As oscillations begin (not yet at “design point”), the following occurs:

- Max temperature reduced from 158F to 138F
- Temperature gradient reduced from 68F to 40F

Under work for publication.

Partnerships

- University Partnerships
  - Pennsylvania State University
    - 1 PhD Student
  - North Carolina Agricultural and Technical State University
    - 1 PhD Student
  - University of California – Irvine
    - 1 PhD Student
  - University of Notre Dame
- Industry Partnerships
  - 1 Small Business and University Partnership (STTR)
- Agency Partnerships
  - NASA’s Jet Propulsion Laboratory

Publications

1. Bashir S. Mekki, Joshua Langer, Stephen Lynch, “Genetic algorithm based topology optimization of heat exchanger fins used in aerospace applications”, International Journal of Heat and Mass Transfer, Volume 170, 2021, 121002, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2021.121002.
2. Sullivan, J., Yu, Z. and Lee, J., 2021. Optical Analysis and Optimization of Micropyramid Texture for Thermal Radiation Control. Nanoscale and Microscale Thermophysical Engineering, 25(3-4), pp.137-152.
3. McNichols, E.O., Jones, S.M., Mirhashemi, A., Juangphanich, P., and Shyam, V. (2021). Preliminary Study of Heat Pipe Turbine Vane Cooling in the NASA N+3 Reference Engine, Proceedings of the ASME Turbo Expo, GT2021-59352, 7-11 June 2021.
4. Sullivan, J., Mirhashemi, A. and Lee, J., 2022. Deep learning based analysis of microstructured materials for thermal radiation control. Scientific reports, 12(1), pp.1-14.
5. Vikram Shyam, Paht Juangphanich, Ezra O. McNichols, Brooke Weborg, Herbert Schilling, Calvin Robinson, Kenji Miki, Manan A. Vyas, Arman Mirhashemi, Joshua Stuckner, Laura Evans, Samaun Nili and Ajay Misra. "IDEAS (Intelligent Design and Engineering of Aerospace Systems)," AIAA 2022-1043. AIAA SCITECH 2022 Forum. January 2022.
6. Bashir S. Mekki and Stephen P. Lynch. "Voxel-Based Topology Optimization of Heat Exchanger Fins," AIAA 2022-2445. AIAA SCITECH 2022 Forum. January 2022.
7. Kenchappa Bharath, Ph.D Thesis: “Development of lightweight multifunctional porous material for aircraft noise mitigation” North Carolina Agricultural and Technical State University, ProQuest Dissertations Publishing, 2022. 29067090.
8. Bharath Kenchappa, Kunigal Shivakumar, and Daniel Sutliff, “Microstructure Controlled Multi-Layer Porous Material Liner Tested on the Advanced Noise Control Fan”, Extended Abstract of a Proposed Paper for AIAA AVIATION Forum and Exposition 12-16 June 2023, San Diego.

Thank you!

Backup Slides

Geometric Properties

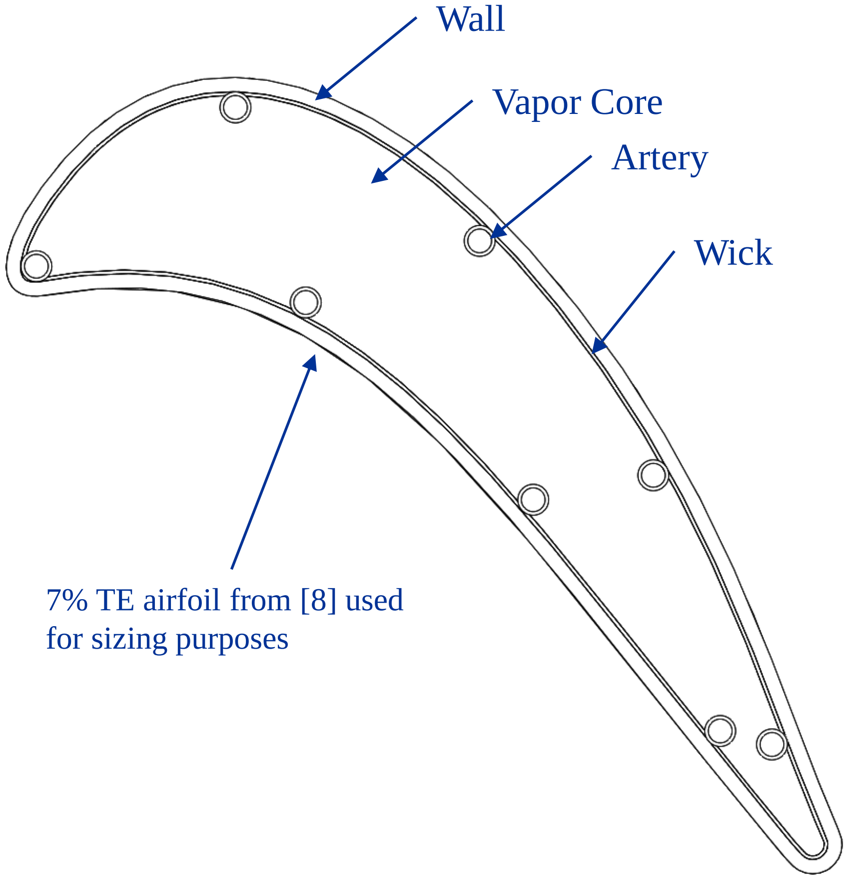
Parameter	Value
Vapor Core Perimeter [m]	0.09888
A_v [m^2]	0.000256
A_w [m^2]	6.1x10^{-5}
A_{wk} [m^2]	1.5 x10^{-5}
$A_{inter,e}$ [m^2]	0.00297
$A_{inter,c}$ [m^2]	0.0157
t_w [mm]	0.60
t_{wk} [mm]	0.15
r_{eff} [µm]	5.6
Wick Type	Composite - Artery with Sintered Perimeter
Number of Arteries	8
r_{art} [mm]	0.50
Working Fluid	Sodium

Based on R_{hp} equations, N+3 sizes, and airfoil geometry

Based on current capabilities of additive manufacturing [7]

Based on heat flux limitation considerations

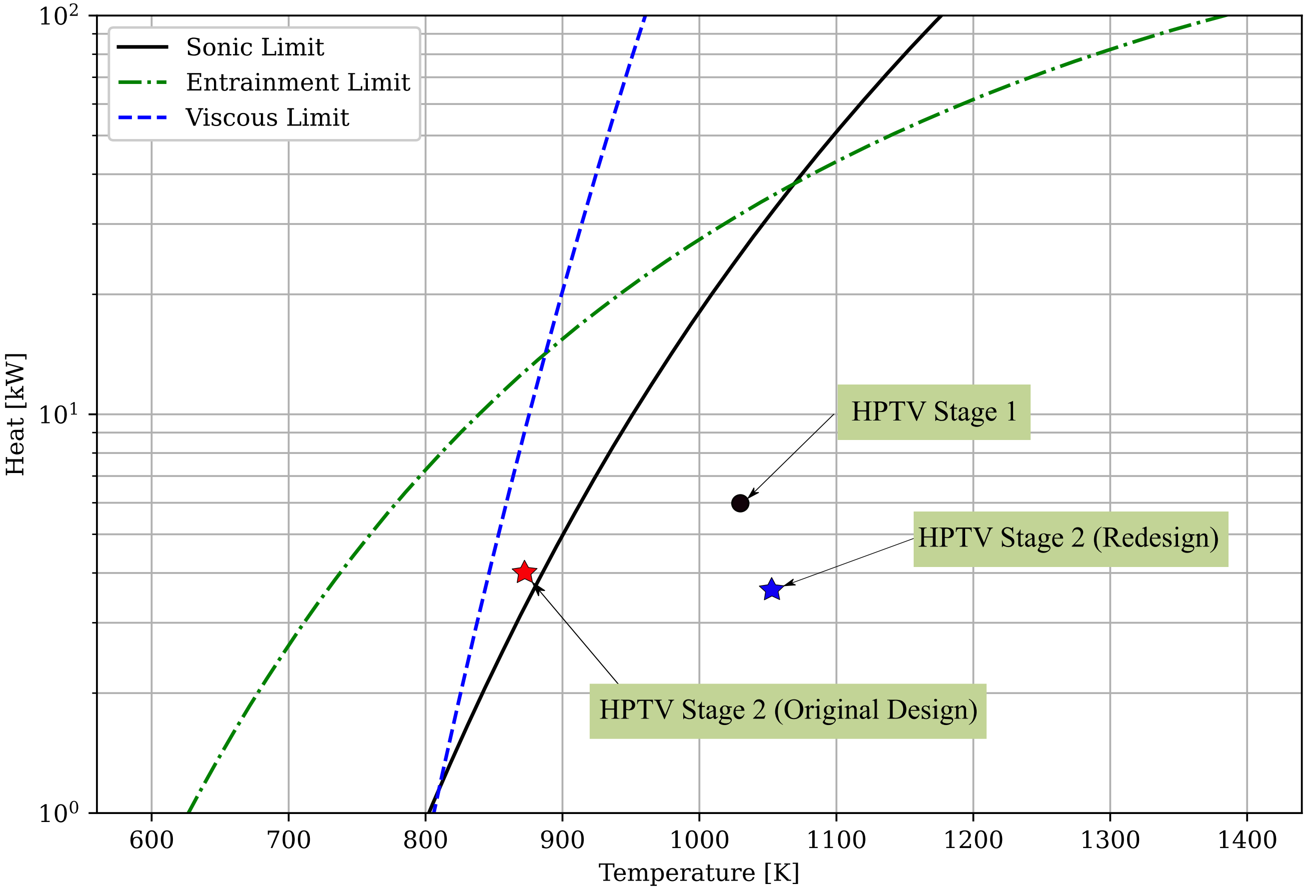
Based on temperatures in N+3 cycle



7% TE airfoil from [8] used for sizing purposes

McNichols, E.O., Jones, S.M., Mirhashemi, A., Juangphanich, P., and Shyam, V. (2021). Preliminary Study of Heat Pipe Turbine Vane Cooling in the NASA N+3 Reference Engine, Proceedings of the ASME Turbo Expo, GT2021-59352, 7-11 June 2021.

Heat Flux Limitations

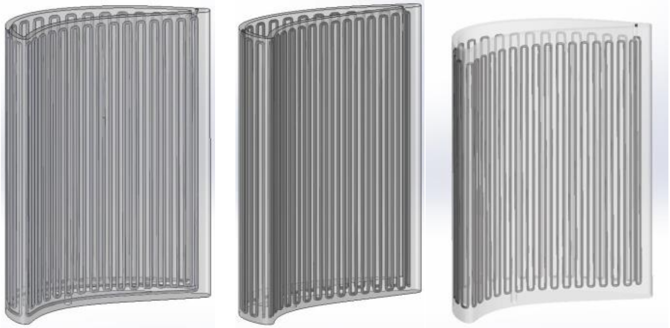


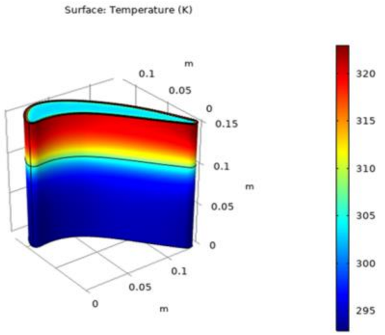
Metric	**HPTV Stage 1**	**HPTV Stage 2 (Original)**	**HPTV Stage 2 (Redesign)**
L_{cond} [m]	$5 \cdot L_{evap}$	$5 \cdot L_{evap}$	$3 \cdot L_{evap}$
R_{hp} [K/W]	0.036	0.088	0.037
T_{hp} [K]	1035	871	1057
T_{vane} [K]	1215	1134	1167
$\dot{Q}_{sonic}$ [kW]	26.5	3.21	33.4
$\dot{Q}_{ent}$ [kW]	32.5	12.7	35.9
$\dot{Q}_{vis}$ [kW]	531	8.66	923
$\dot{Q}$ [kW]	6.04	4.06	3.77

McNichols, E.O., Jones, S.M., Mirhashemi, A., Juangphanich, P., and Shyam, V. (2021). Preliminary Study of Heat Pipe Turbine Vane Cooling in the NASA N+3 Reference Engine, Proceedings of the ASME Turbo Expo, GT2021-59352, 7-11 June 2021.

Summary

Design and Analysis Tool Development

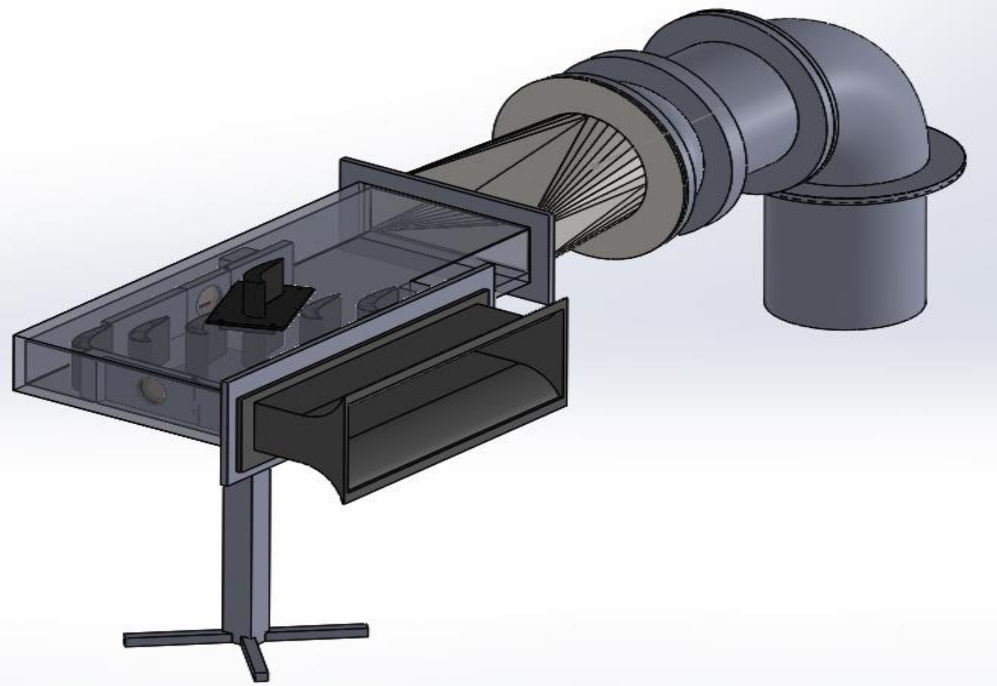




Tools consist of:

- 0-D for Initial Sizing (thermal resistance network)
- 3-D Multiphysics (ignoring external aero)
- 3-D Multiphysics (coupling with external aero)

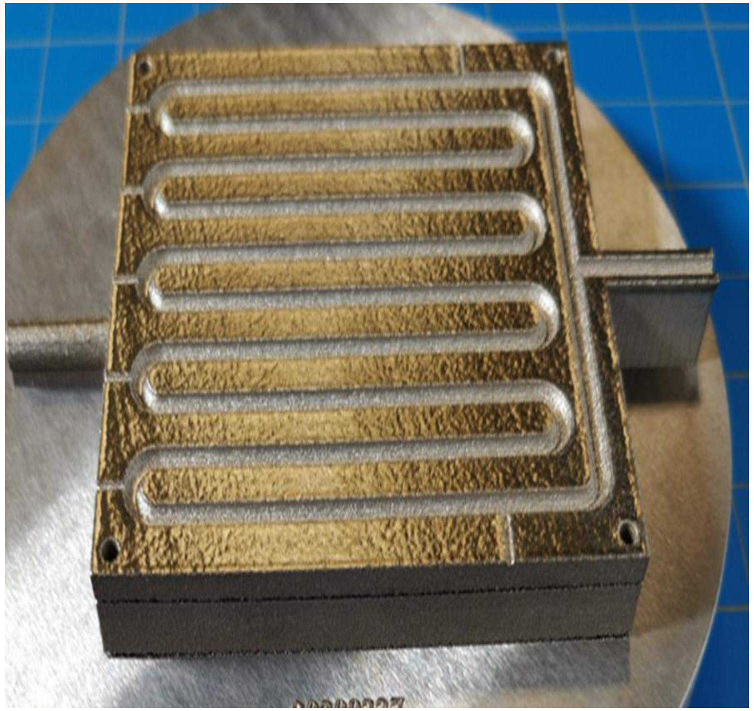
Low Temperature Aero/Thermal Testing



Main Points:

- Goal of tests are to assess performance/stability, and to compare to 3-D Multiphysics models (both levels of fidelity)
- For OHP designs, more emphasis on stability rather than comparison to tools

High Temperature Coupon Testing



Main Points:

- Data for high temperature OHPs is scarce. Only 1 published paper with this data (in 2020)