# 40 kW Turbo-Alternator Hybrid-Electric Range Extender

## AHS Transformative Vertical Flight Concepts Workshop

Rory Keogh, Ph.D. | Lead Propulsion Engineer

August 2015

metis design

*structural health monitoring*
*multi-functional materials*
*lean enterprise solutions*

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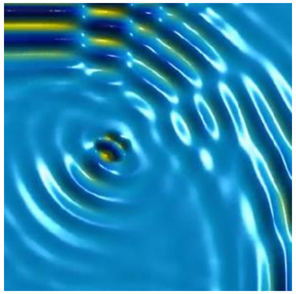
# Metis Design Corporation (MDC)

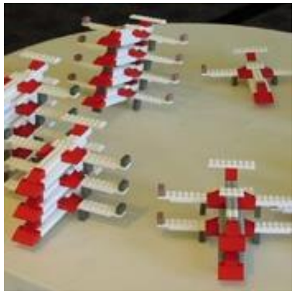
## Overview

- Introduction to Metis Design
- Project Background
- Technology Overview
  - Turbomachinery and generator
  - Waste heat recovery (recuperation)
  - Performance metrics and scalability
  - Noise
- Summary

# Metis Design Corporation (MDC)

- **Offer novel multi-disciplinary defense, aerospace & energy solutions**





- Diverse engineering staff
  - solid fundamental principles (10/14 staff hold Ph.D.'s)
  - hands-on experience from 42 SBIR/BAA contracts over 12 years
  - Boston MA headquarters & satellite offices in CA & NM

- MDC has invented multiple disruptive technologies
  - **Microturbine range extender**
  - Carbon nanotube (CNT) de-icing & anti-icing system for composite wings
  - Distributed SHM/HUMS sensor digital infrastructure

# Background Projects

Micro-Turbofan for small scale high performance aircraft

DARPA

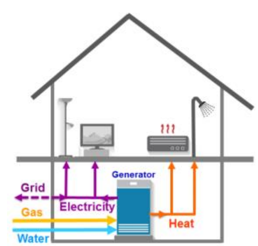
Turbo-generator to flight test sub-scale electric aircraft

NASA

Microturbine battery electric vehicle range extender

BMW

Microturbine for residential combined heat and power




arpa·e
CHANGING WHAT'S POSSIBLE

# Metis Design Corporation (MDC)

- Rory Keogh
  - Joined Metis Design in 2010 to lead DARPA funded jet engine project
  - B.E. Mech. from NUI Galway, M.S. & Ph.D. from MIT Dept. of Aero and Astronautics
  - 5 years experience at Boeing (Mechanical Systems) and 6 years management consulting
- Greg Thomas
  - Joined Metis Design in 2010 to work on DARPA funded jet engine project
  - M.Eng. and D.Phil. in Engineering Science from the University of Oxford
  - Worked at McLaren international and Schlumberger
- Seth Kessler
  - Founded Metis Design in 2002 & completed over 40 govt. research contracts (SBIR & BAA)
  - B.S., M.S. & Ph.D. from MIT Department of Aeronautics and Astronautics
  - Worked at Lockheed Skunk Works
- Todd Engel
  - B.S. Mechanical Engineering UCSB 2005, M.S. Mechanical Engineering USC 2010
  - 10 years at Rolls Royce / Hyper-Therm High Temperature Composites
- Antoine Corbeil
  - B.Eng. Mech. Royal Military College of CA 1995, M.Sc. Mech. Eng. University of Ottawa 2010
  - 19 years P&W Canada / Rolls Royce Canada / Ingersoll Rand / Brayton Energy Canada



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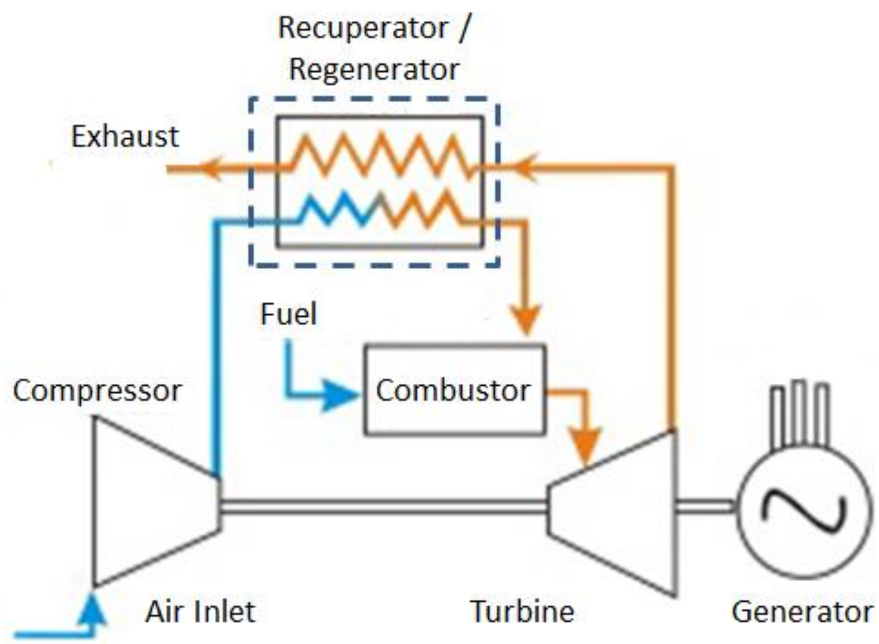
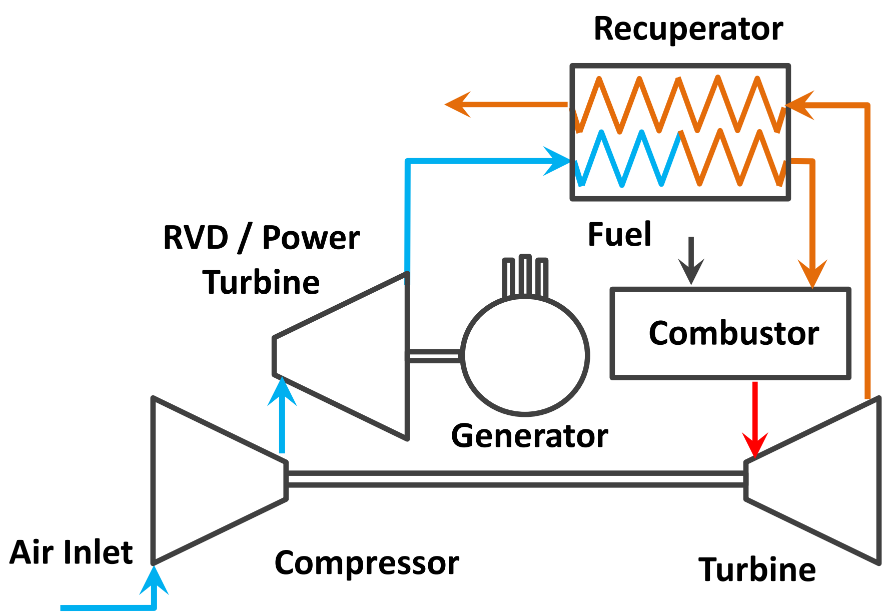
# Microturbine Systems

## State-of-the-art

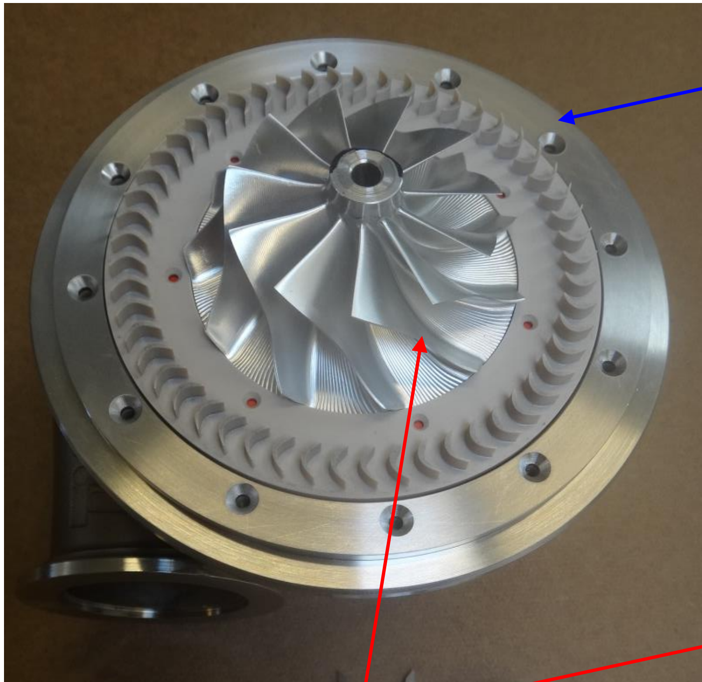



## Metis Design




**Unique two-spool gas turbine with pre-combustion power turbine**

# Turbomachinery Innovation



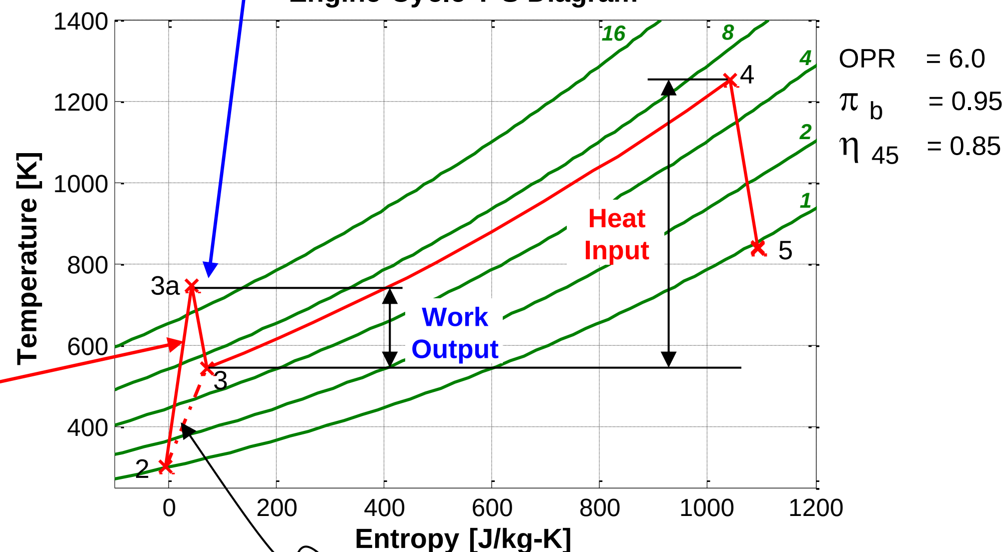
- High pressure ratio centrifugal impeller
  - ➢ Design efficiency 92 - 95% (w/o tip gap loss)

- Aerodynamically coupled co-rotating power turbine
  - ➢ Design efficiency ~92%
  - ➢ Gearing ratio of 2 to 4

**Component Efficiency**

**Cycle Efficiency**

**Engine Cycle T-S Diagram***




## Equivalent Compression Process

$\pi_{23a} = 16$

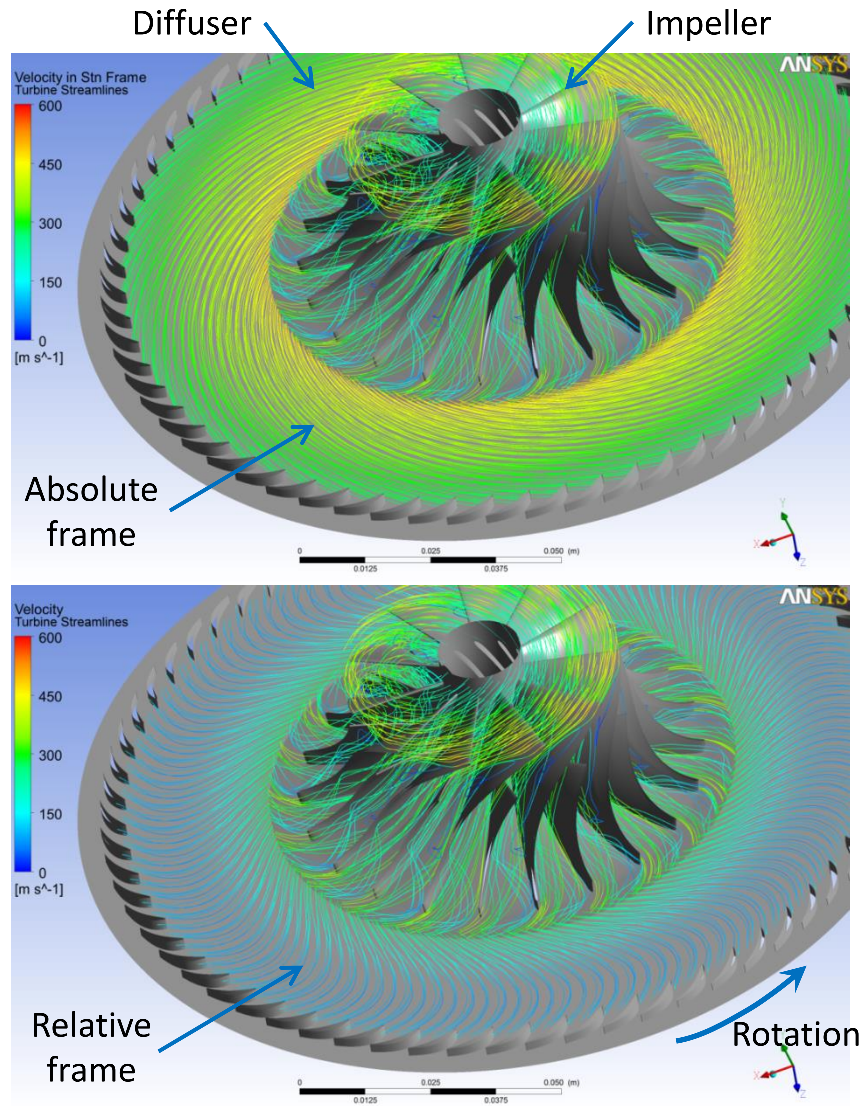
$\pi_{23} = 6.3$

$\gamma = 1.4$

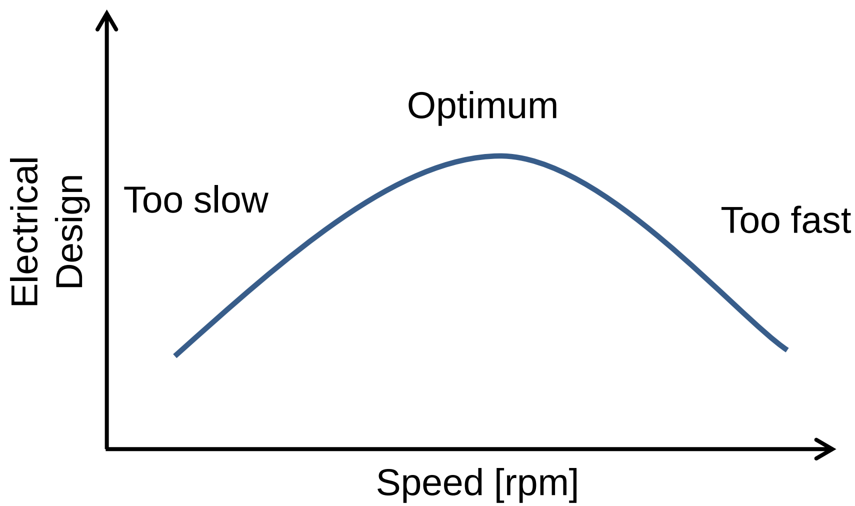
| $\eta_{23a}$ | $\eta_{3a3}$ | $\eta_{23}$ |
|---|---|---|
| 0.95 | 0.95 | 0.90 |
| 0.95 | 0.92 | 0.88 |
| 0.92 | 0.92 | 0.85 |

# Turbomachinery Innovation

- ~50% impeller / 50% diffuser pressure rise
- ~80% impeller pressure rise comes from loss free centrifugal acceleration (efficiency 92-95%)
- Diffusers are very lossy (power loss proportional to $V^3$)
- Rotating diffuser relative velocity in the diffuser can be halved and streamtube length can be reduced (by ~70%)
- Power turbine can be extract work at ¼ to ½ of the speed of the impeller with similar efficiency to microturbines



# Generator Design Space

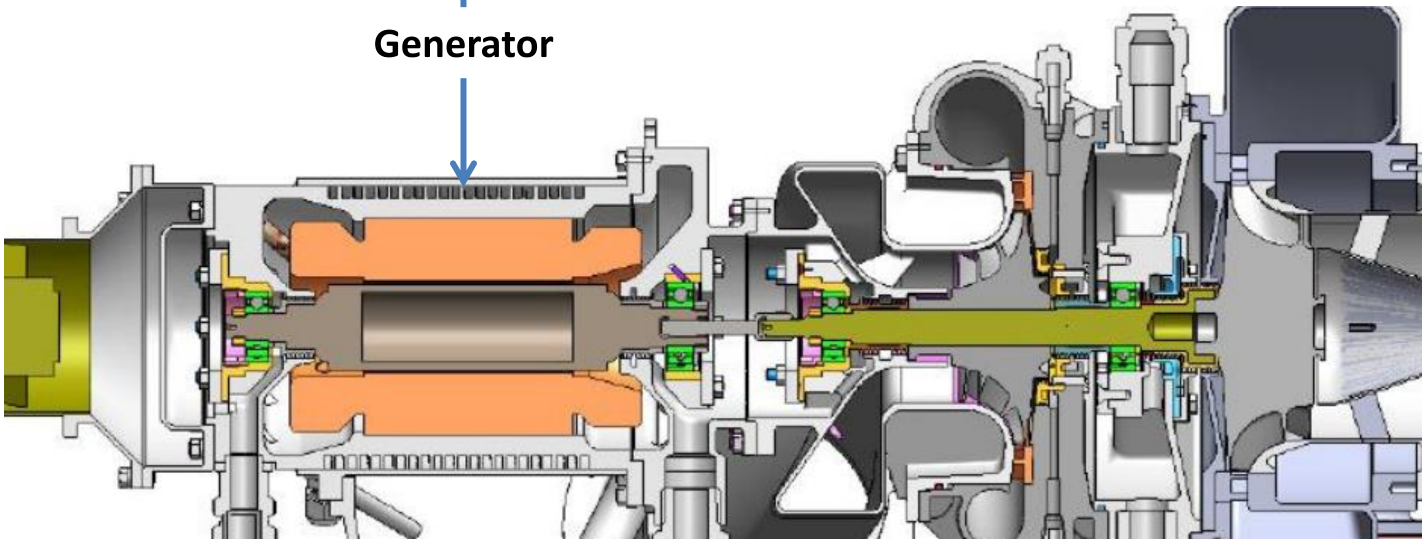



| Feature | Slow | Medium | Fast |
|---|---|---|---|
| Weight | ✗ | ✓ | ✓ |
| Efficiency | ✗ | ✓ | ✓ |
| Cooling | ✗ | ✓ | ✓ |
| Bearings | ✓ | ✓ | ✗ |
| Rotordynamics | ✓ | ✓ | ✗ |
| Cost | ✓ | ✓ | ✗ |

Optimum generator speed

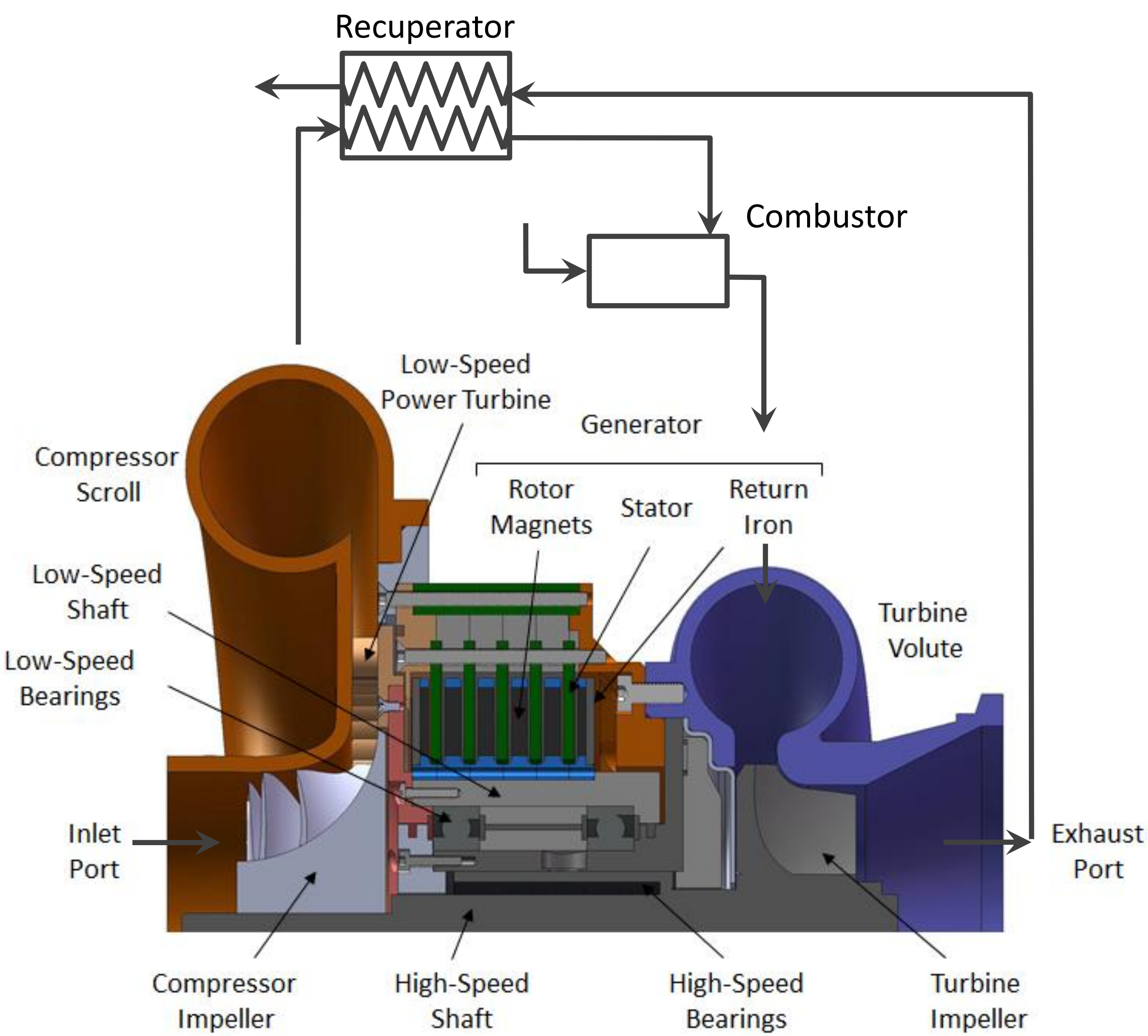
# Generator / Turbomachine Integration

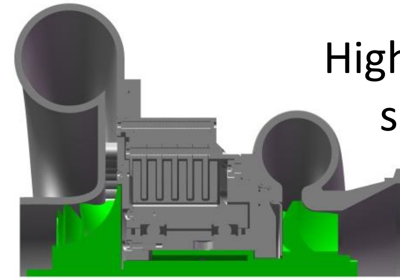
**Capstone C30**

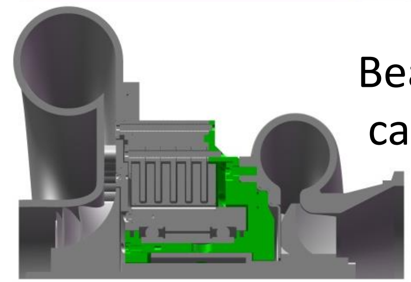


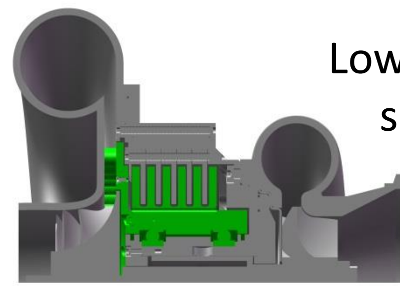

**R-Jet (aviation)**

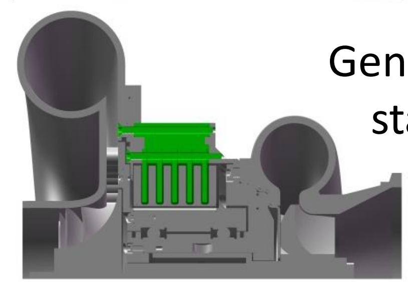
# Turbomachinery and generator (Phase I)



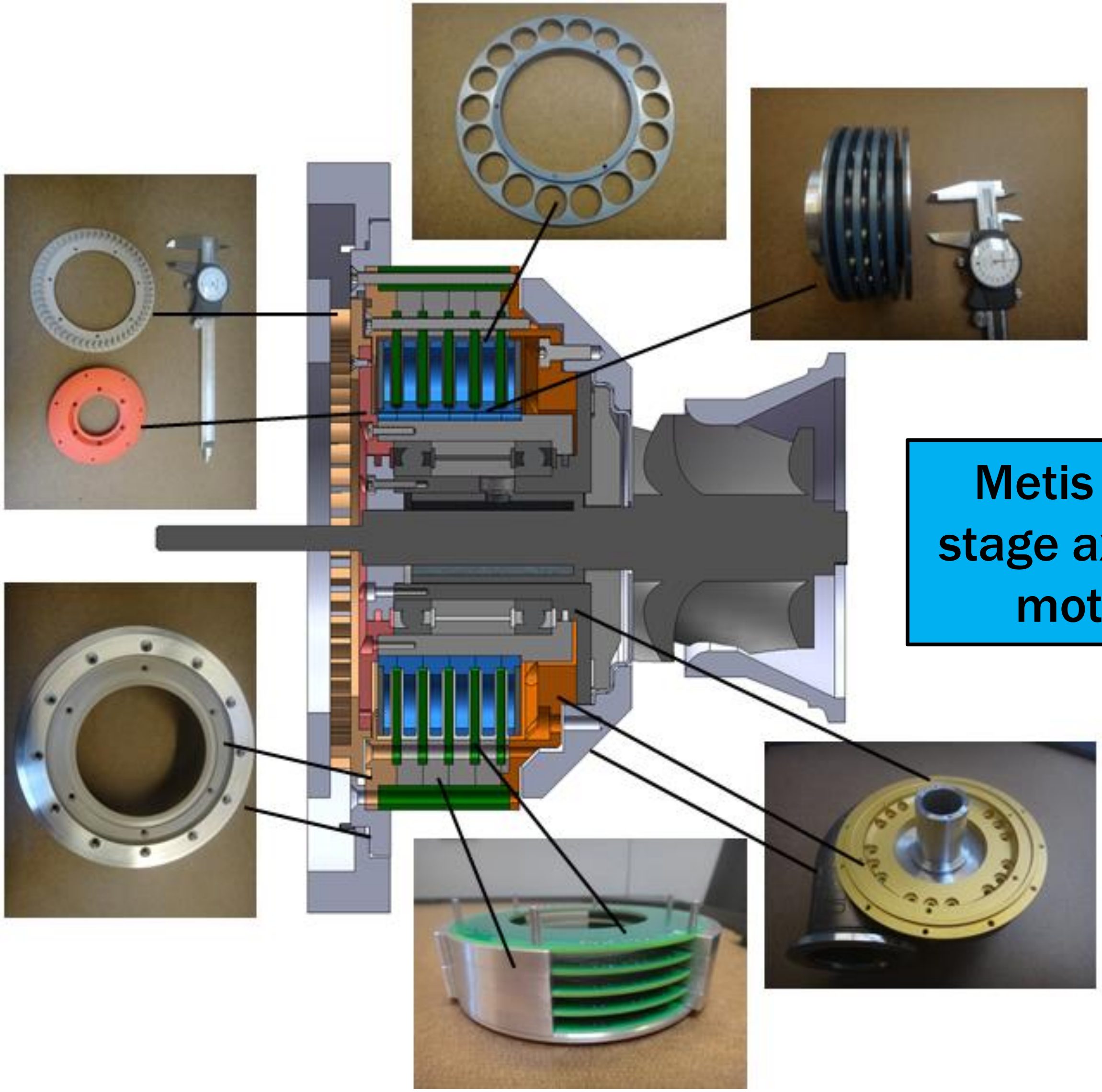



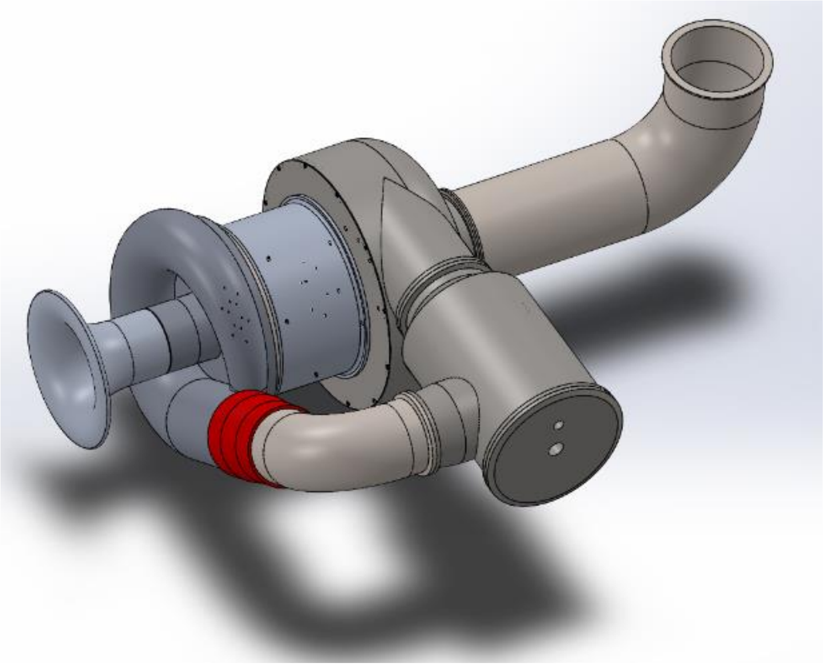



# Metis Generator (Phase I)

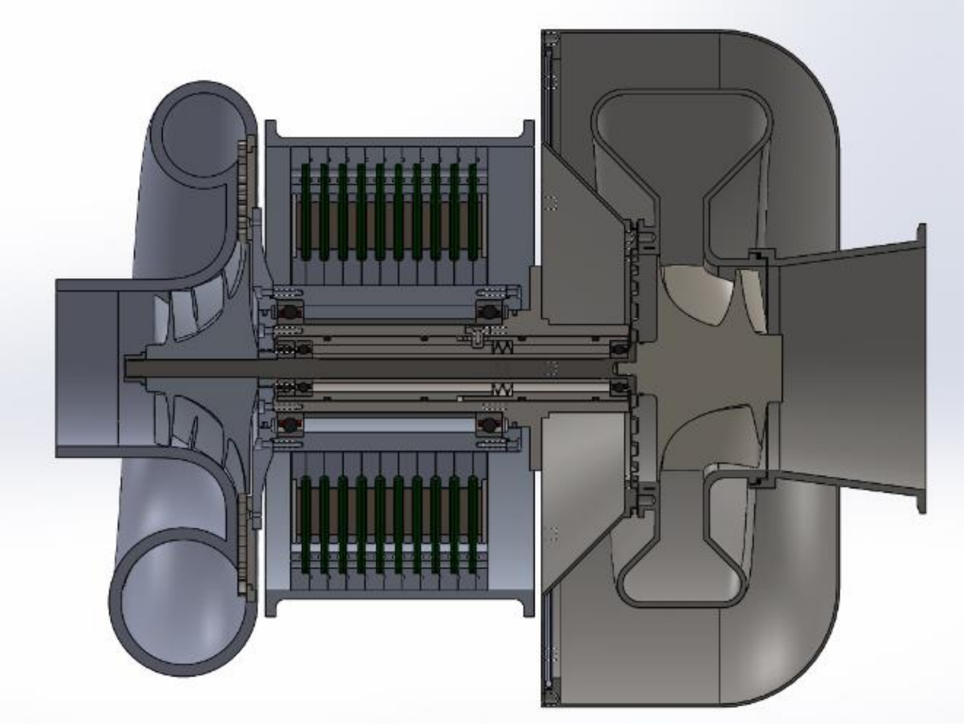


Metis low cost multi stage axial flux coreless motor/generator

# Turbomachinery and generator (Phase II)

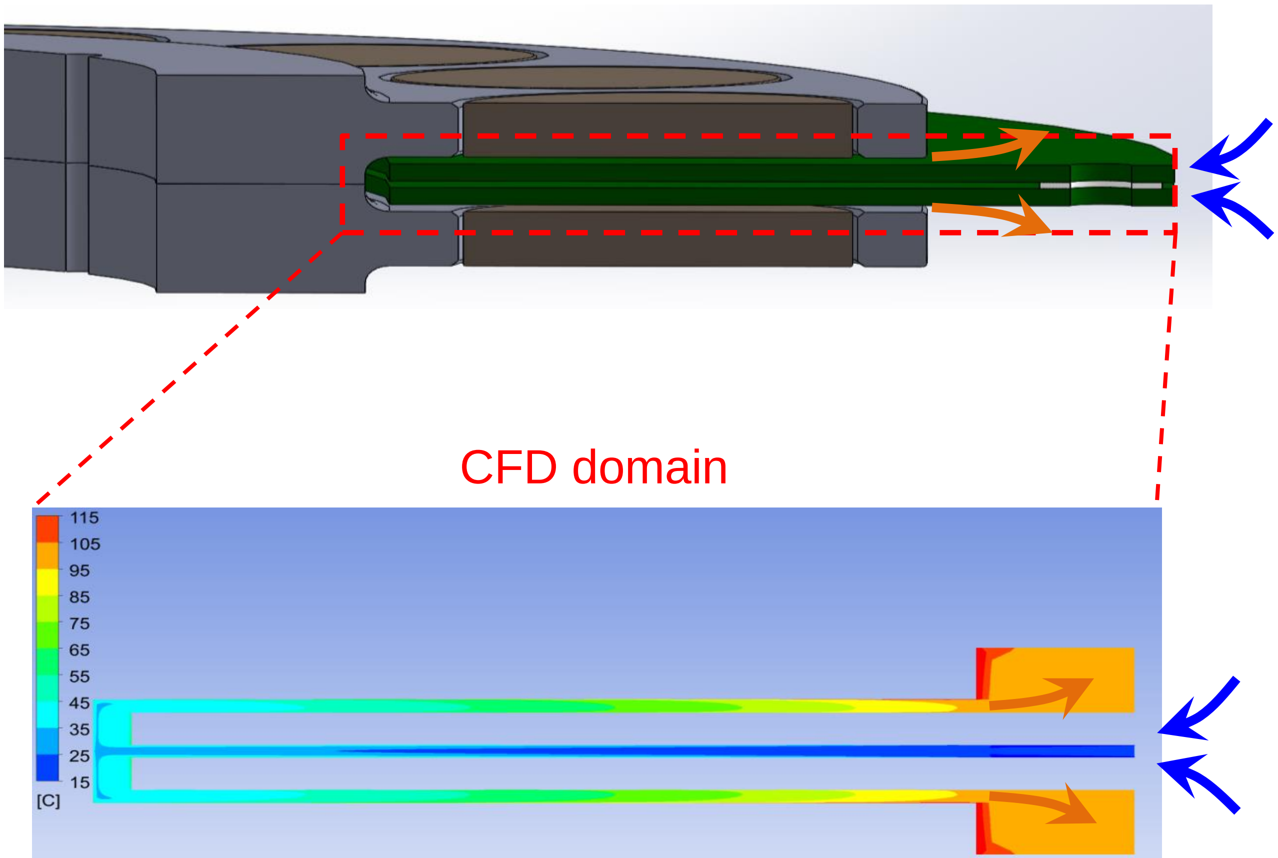


Non-recuperated turbo-alternator



Turbo-alternator cross-section

# Generator Thermal Control



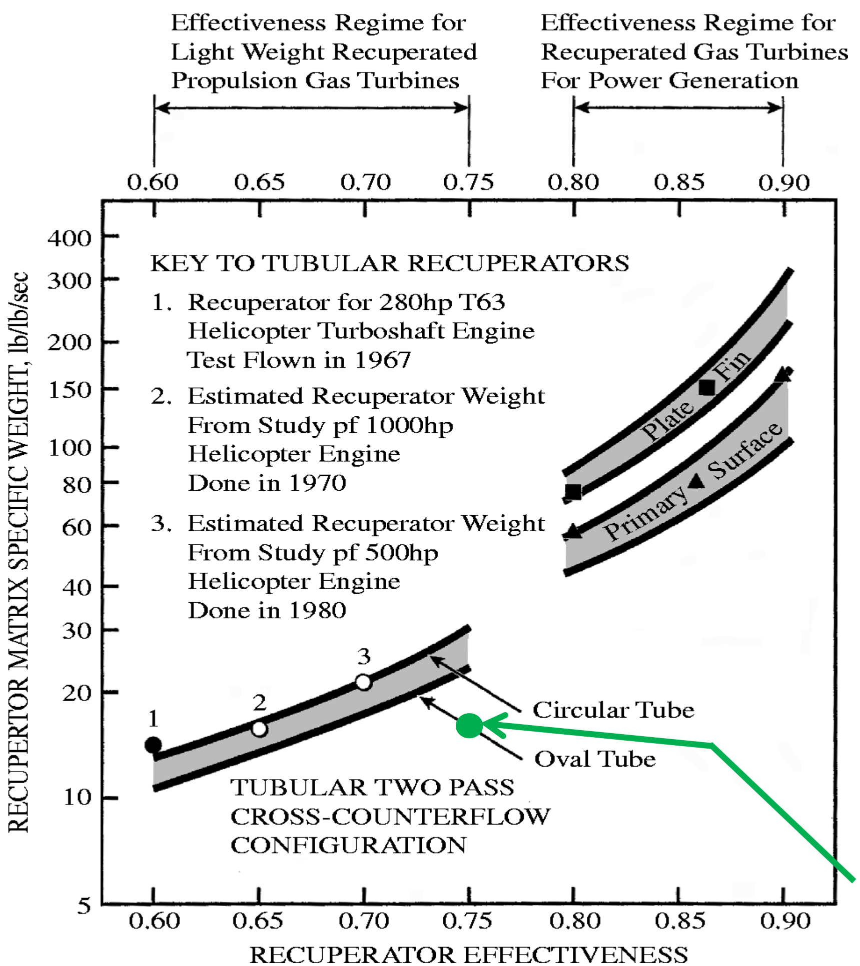

**CFD simulation:**

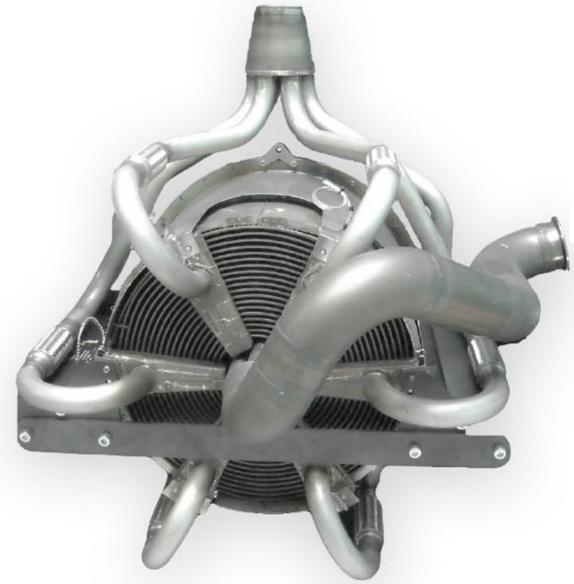
- Stator wall heat flux of 5.85kW/m²
- Rotor wall speed of 40krpm
- Inlet temperature of 15°C
- Only modelling the cooling passage

**Results**

- Stator heat loss = 160W
- Stator temp = 54°C av, 100°C max
- Rotor tempe = 66°C av, 95°C max

# Recuperator Summary



## GAP Waste Heat Recuperator

### Designed and operated within a FP7 CleanSky project

**Overall dimensions:**

Global HxLxW: 780x760x960mm
Core diameter: ~420mm

Global Weight: 50kg
Core only: ~30kg

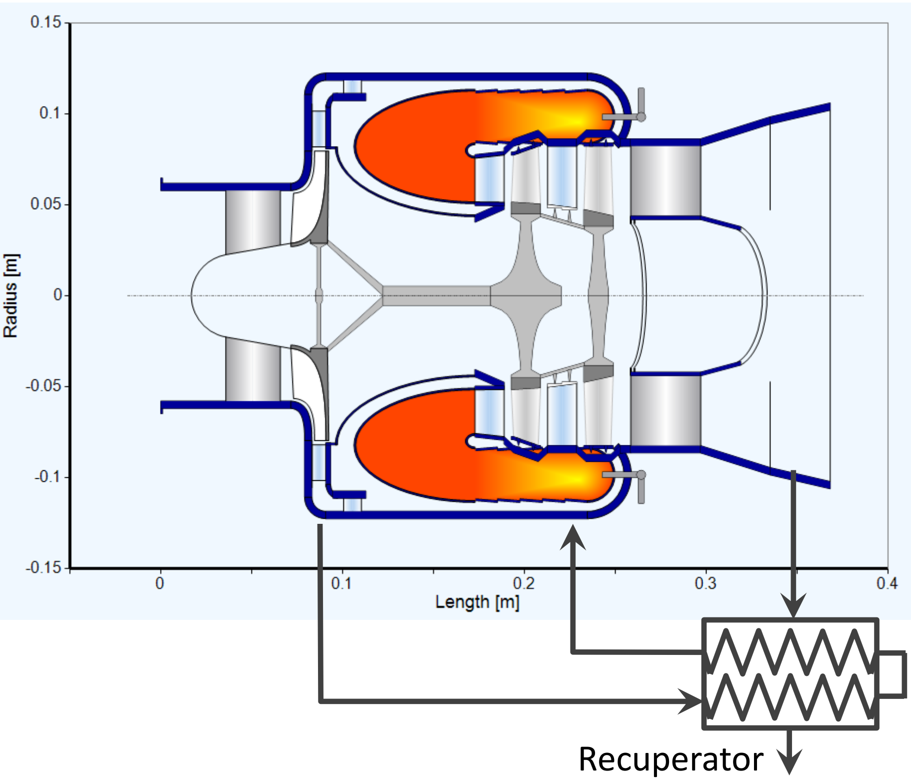
**Overall features:**

Nominal Effectiveness: 75%
Nominal Power Range: 90kW
Temperature Range: from 200°C to 650°C

# Performance Summary

| Parameter | NASA | High OPR | Unit |
|---|---|---|---|
| Power (SLS/18kft) | 40/23 | 56/32 | kW |
| OPR | 3.0 | 4.5 | - |
| TIT | 950 | 1050 | C |
| Recuperator Eff. (SLS/18kft) | 60/70 | 60/70 | % |
| Electrical Eff. (SLS/18kft) | 21/26 | 24/31 | % |
| SFC (SLS/18kft) | 391/319 | 319/267 | g/kW.hr |
| Specific Weight | 2.4 | 3.2 | kW/kg |
| Specific Volume | 2.2 | 3.1 | kW/L |

# Preliminary 300kW Configuration




| Parameter | Value | Unit |
|---|---|---|
| Power (SLS/18kft) | 300/168 | kW |
| OPR | 4.5 | - |
| TIT | 1050 | C |
| Recup. Eff. (SLS/18kft) | 60/70 | % |
| Elect. Eff. (SLS/18kft) | 32/37 | % |
| SFC (SLS/18kft) | 262/226 | g/kW.hr |
| Sp. Weight | 4.4 | kW/kg |
| Sp. Volume | 4.9 | kW/L |

- **Reverse flow annular combustor**
- **Uncooled two stage axial turbine**
- **Preliminary estimates using GasTurb12**

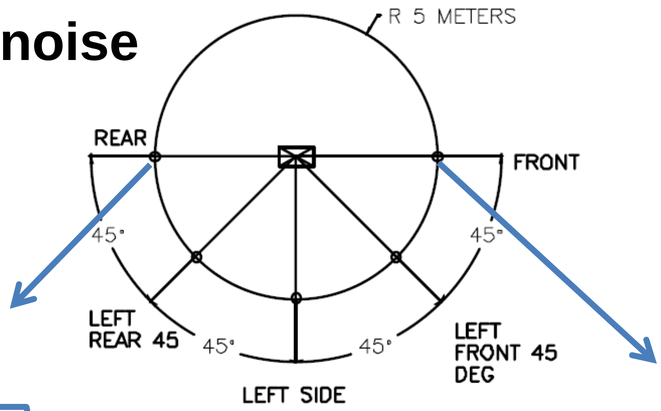
# Metis Design Corporation (MDC)

## Noise Source Benchmarking

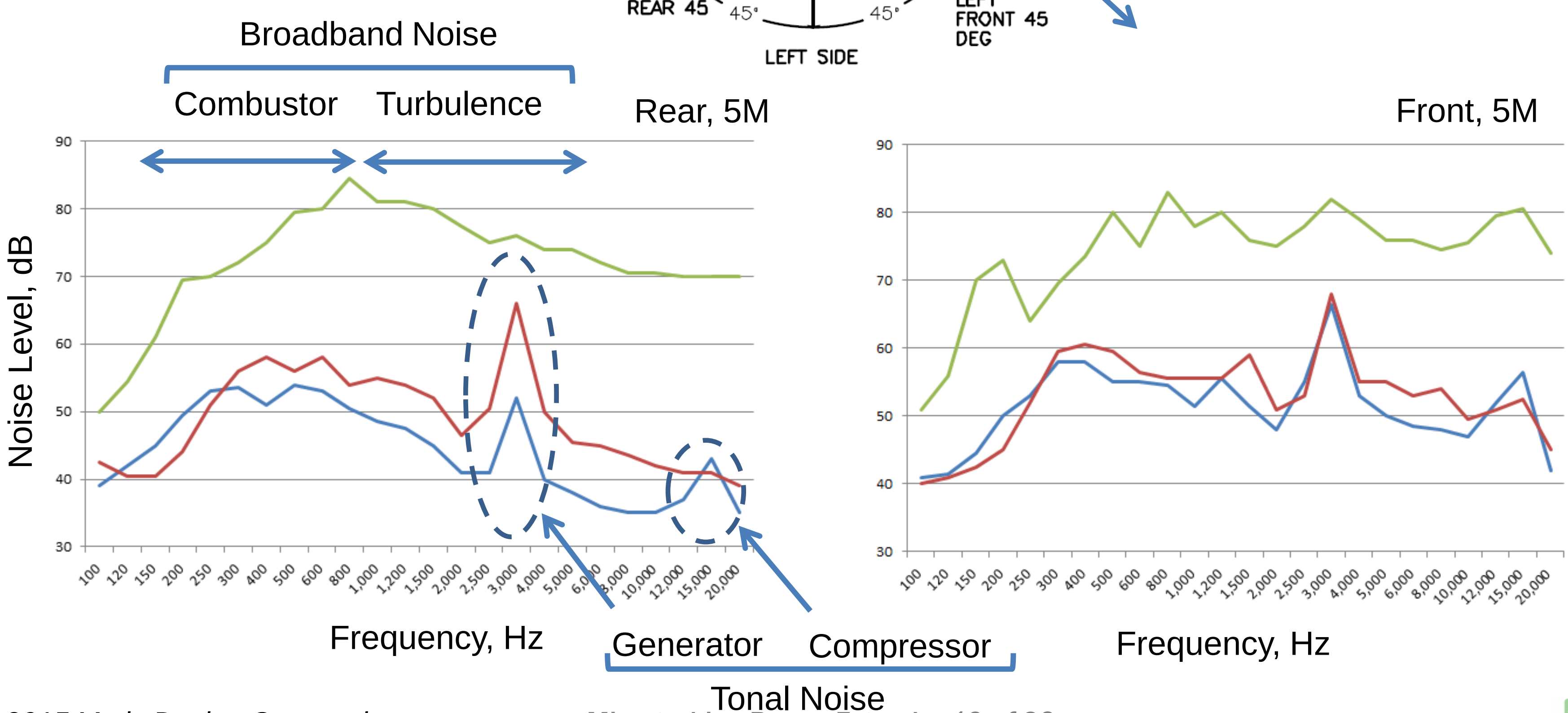
| Noise Source | Capstone C30 | Metis 40kW |
|---|---|---|
| Airflow turbulence in intake, compressor, flow passages, turbine and exhaust | Broadband 1,000 to 5,000 Hz | Similar |
| Compressor and turbine Blade passing tones | Comp: 14,400 kHz<br>Turbine: 20,800 kHz | Similar |
| Generator rotor-stator tonal interaction | 3,200 Hz | Minimal – ironless core stator |
| Combustion | Broadband peaks from 400 to 800 Hz | Less noise – lean premixed combustion |
| Noise pathways | Inlet, outlet and case radiated | Inlet, outlet and case radiated |

# Noise Level Benchmarking

## Capstone C30 measured noise




No recuperator
Recuperator
Recuperator + exhaust silencer

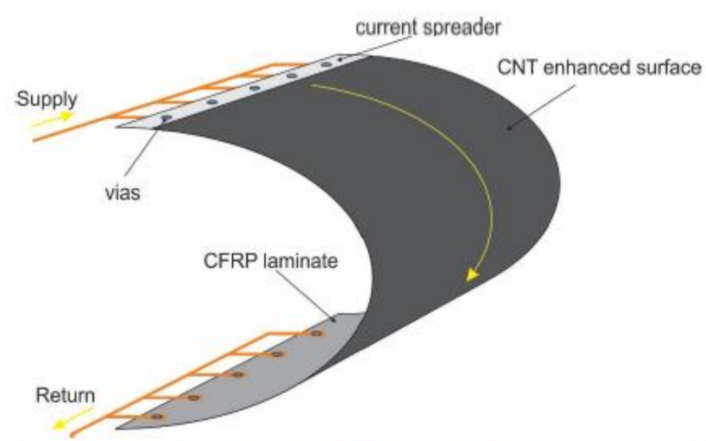


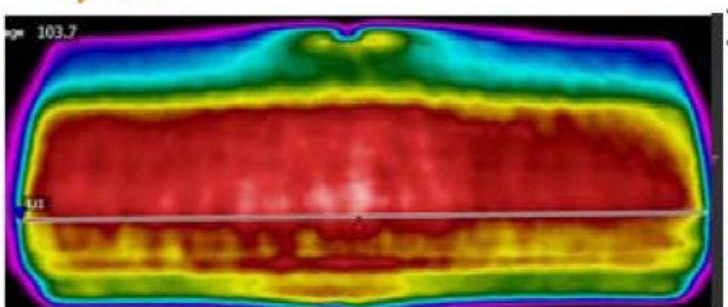
# Conformal Multi-functional Assemblies

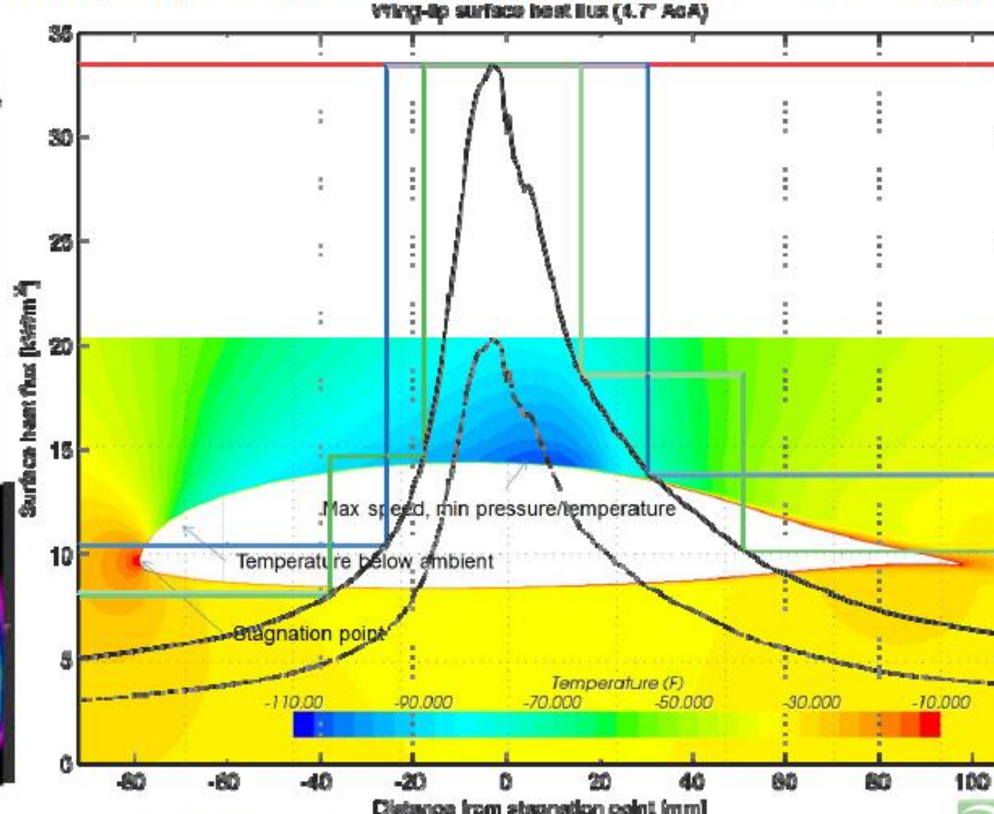
- Conformal assemblies for composite & metallic host structures
  - ➢ Central carbon nanotube (CNT) layer is core to these properties
  - ➢ Surrounded by electrically insulating layers (film adhesive and/or GFRP)
  - ➢ Selective electrodes integrated to steer current flow
- No impact to physical structure, 100 - 200 μm & 5 - 10 $g/m^2$
  - ➢ Can be co-cured with composite laminate
  - ➢ Can be installed over composite or metallic skin in secondary process
- Enable multi-functional capabilities: heating, sensing, conducting

# Ice Protection Systems (IPS)

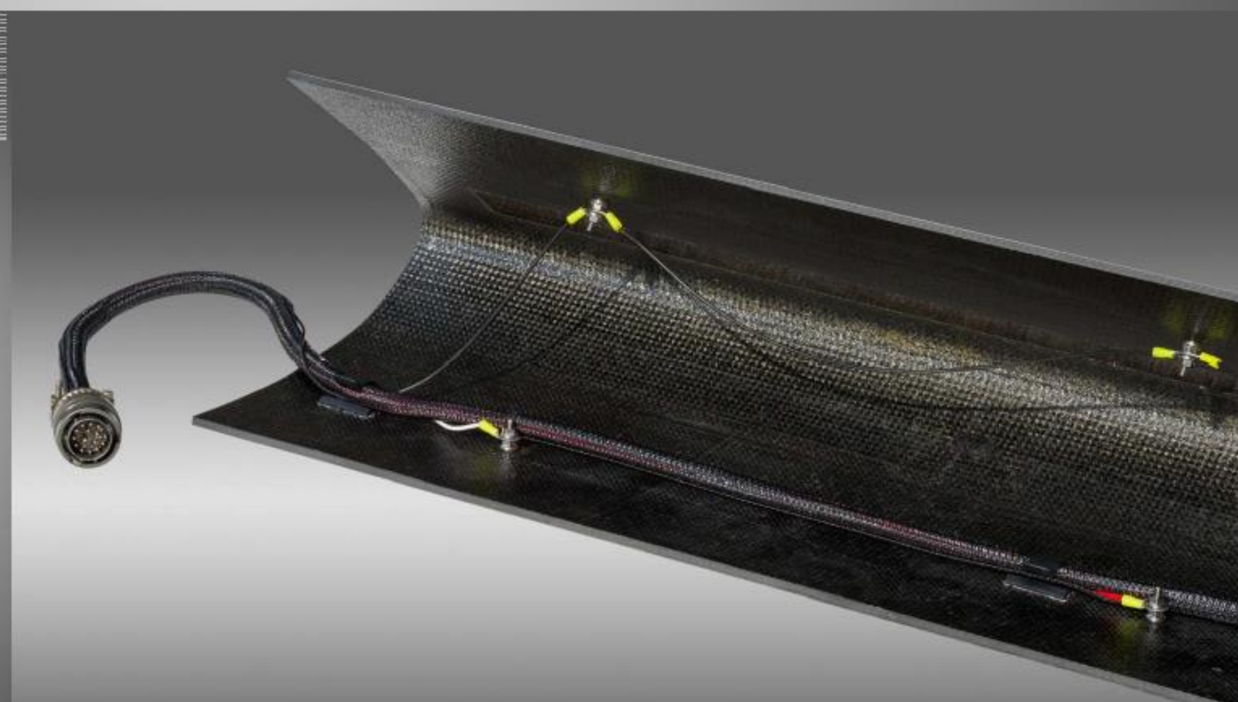
- Quasi-uniform, efficient resistive heating across large areas
- Heat delivered to iced surface interface to reduce energy required
- Tunable resistivity (material property) for optimal power setting



# Triton UAS Full-Scale Wing-Extension Integration



# CNT-IPS Benefits

- Manufacturing
  - CNT has similar negative CTE to CFRP, eliminate warpage & residual stress
  - Thin in nature so can be inserted anywhere in laminate without LE impact
  - Can drill countersunk attachment points ANYWHERE without inserts
- Weight
  - CNT sheet are 50 $\mu$m → 5-10 gsm of heater area
  - Electrodes are 50 $\mu$m → 10-15 gsm of heater area
  - Total 10-25 gsm of heater area→ ~3 g for a heating zone on Triton
  - Approximate total system weight over full 150’ wingspan of 1 kg
- Power
  - Simple to calculate using patch resistance and input voltage
  - Can make very efficient by matching resistance around chord profile
  - Less than 50% of uniform power for Triton

# CNT-IPS Ice Tunnel Testing

- Ice tunnel testing performed per NAVAIR specified test matrix
  - Heavy icing conditions (125 mph, -22°F, 1.1% LWC)
  - CNT-IPS fully integrated for Predator UAV tail (1 meter span by 10% chord)
- Testing validated predicted capabilities for CNT as heaters
  - Effective for de-ice without mechanical assist > 0°F, with mechanical < 0°F
  - Effective for anti-icing (maintaining skin temperature just above freezing)

# Summary

- A highly integrated two spool turbine and generator enable a very compact, high power density gas turbine generator
- Moderate levels of recuperation (60-70%) dramatically reduce SFC while maintaining high power density
  - ➢ SFC and power density improve at increased power levels (100's of kW)
  - ➢ Recuperation dramatically reduces noise emitted from the gas turbine generator
- Microturbine testing planned for December 2015

# Technical & Business Contact

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