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Real-Time Closed Loop Modulated Turbine Cooling

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NASA Aeronautics Programs

Fundamental Aeronautics Program

Conduct fundamental research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment

Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.

Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.

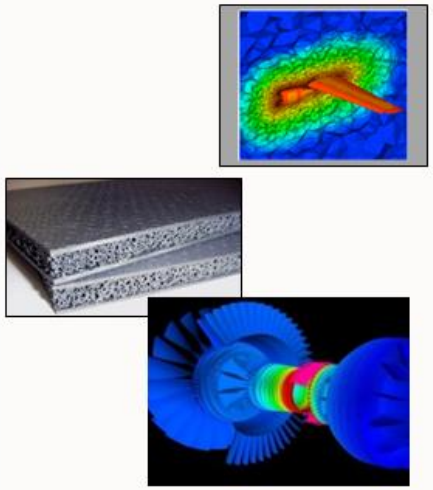
Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.

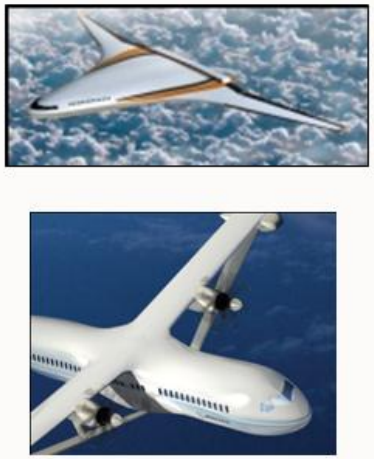
FA Program Organization Structure

Fundamental Aeronautics Program Office

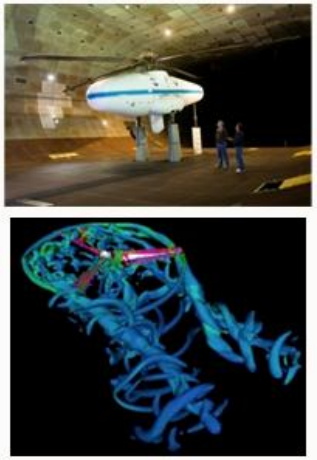
Aeronautical Sciences Project



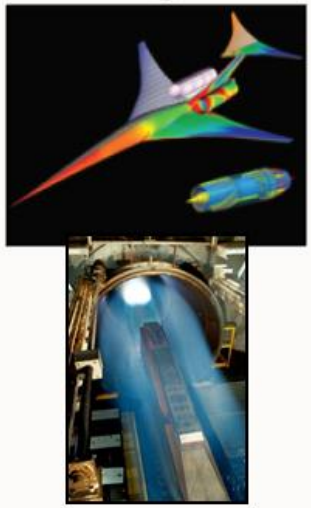
Fixed Wing Project



Rotary Wing Project



High Speed Project



Aeronautical Sciences (AS)
Enable fast, efficient design & analysis of advanced aviation systems from first principles through physics-based tools, methods, & cross-cutting technologies.

Fixed Wing (FW)
Explore & develop technologies and concepts for improved energy efficiency & environmental compatibility of fixed wing, subsonic transports

Rotary Wing (RW)
Enable radical changes in the transportation system through advanced rotary wing vehicles concepts & capabilities.

High Speed (HS)
Enable tools &technologies and validation capabilities necessary to overcome environmental & performance barriers to practical civil supersonic airliners.

NASA Subsonic Transport System Level Metrics

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TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

N2A Turbofan – HPT Cooling Schematic

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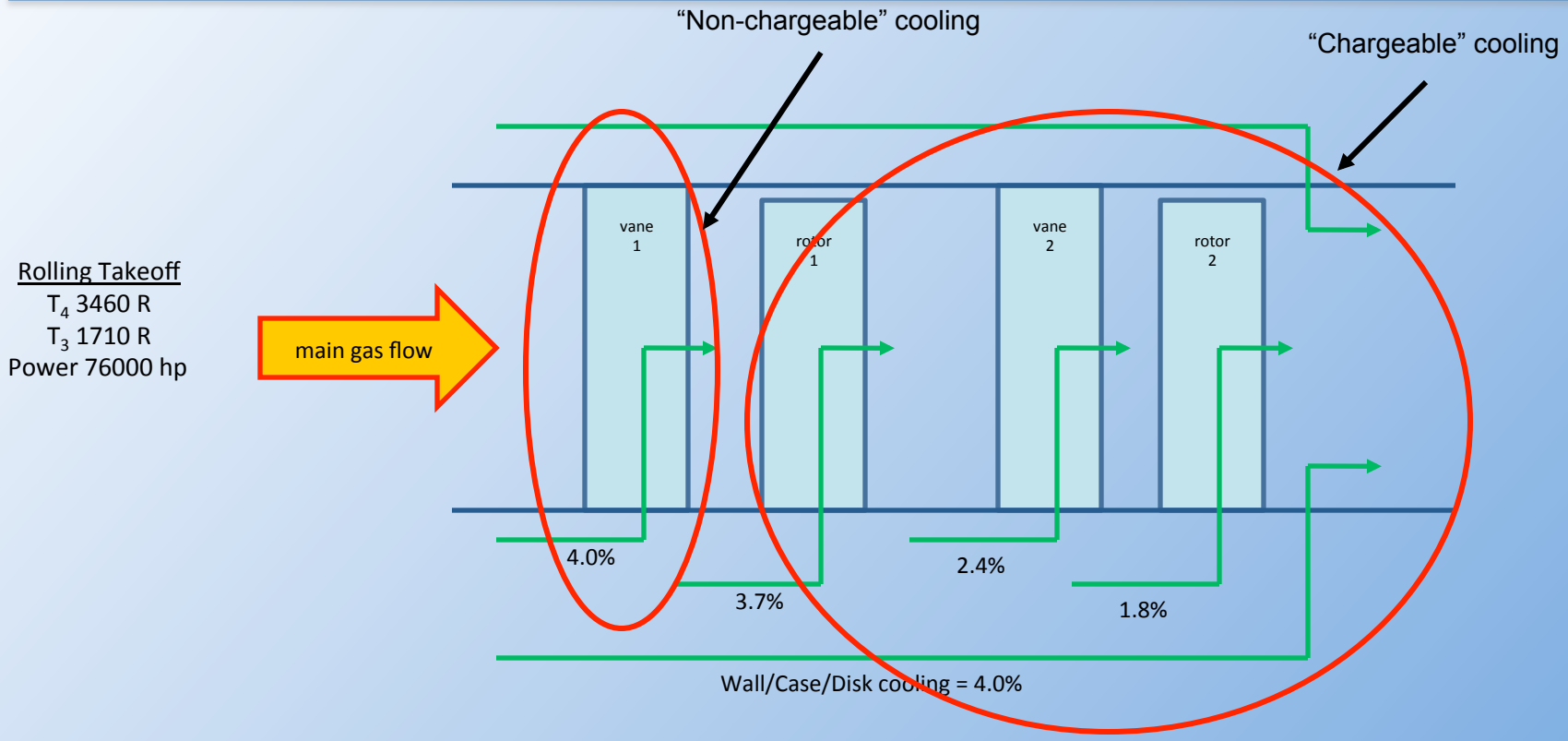

- Cooling levels defined at max. cycle temperatures (RTO for subsonic engines)
- Non-chargeable cooling flow has little/no impact on cycle performance
  - All flow available to perform work through HPT rotors
- Further downstream flow is injected, more penalizing
  - Penalty mitigated somewhat due to temperature decrease through machine

Reference N2A engine assumes high temperature metallics/TBCs – no CMCs

Benefits of Modulating Cooling

- 12% cooling reduction leads to 3.6% Fuel Burn reduction
- If 5% core flow saved, 1-1.5% fuel burn reduction
- Currently this can be scheduled
  - Need safety margin
  - Unable to adjust for changes in environment, reduction of coolant flow due to clogging etc.
  - Could save 1% fuel burn using this method after trading weight
- Would be nice to modulate cooling based on real-time conditions
  - Additional 1.5% fuel burn savings possible.

Potential Fuel Burn Benefit

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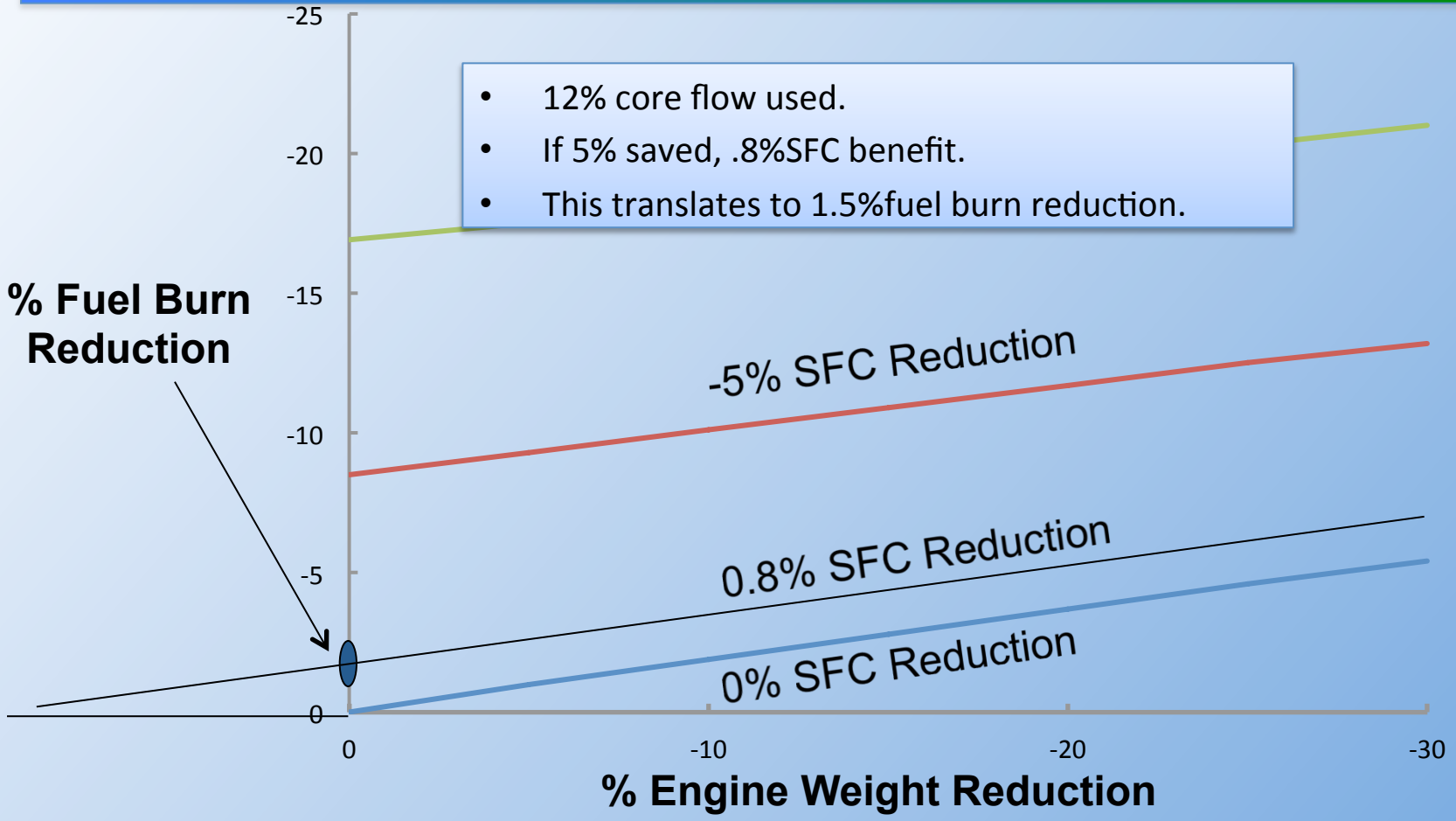


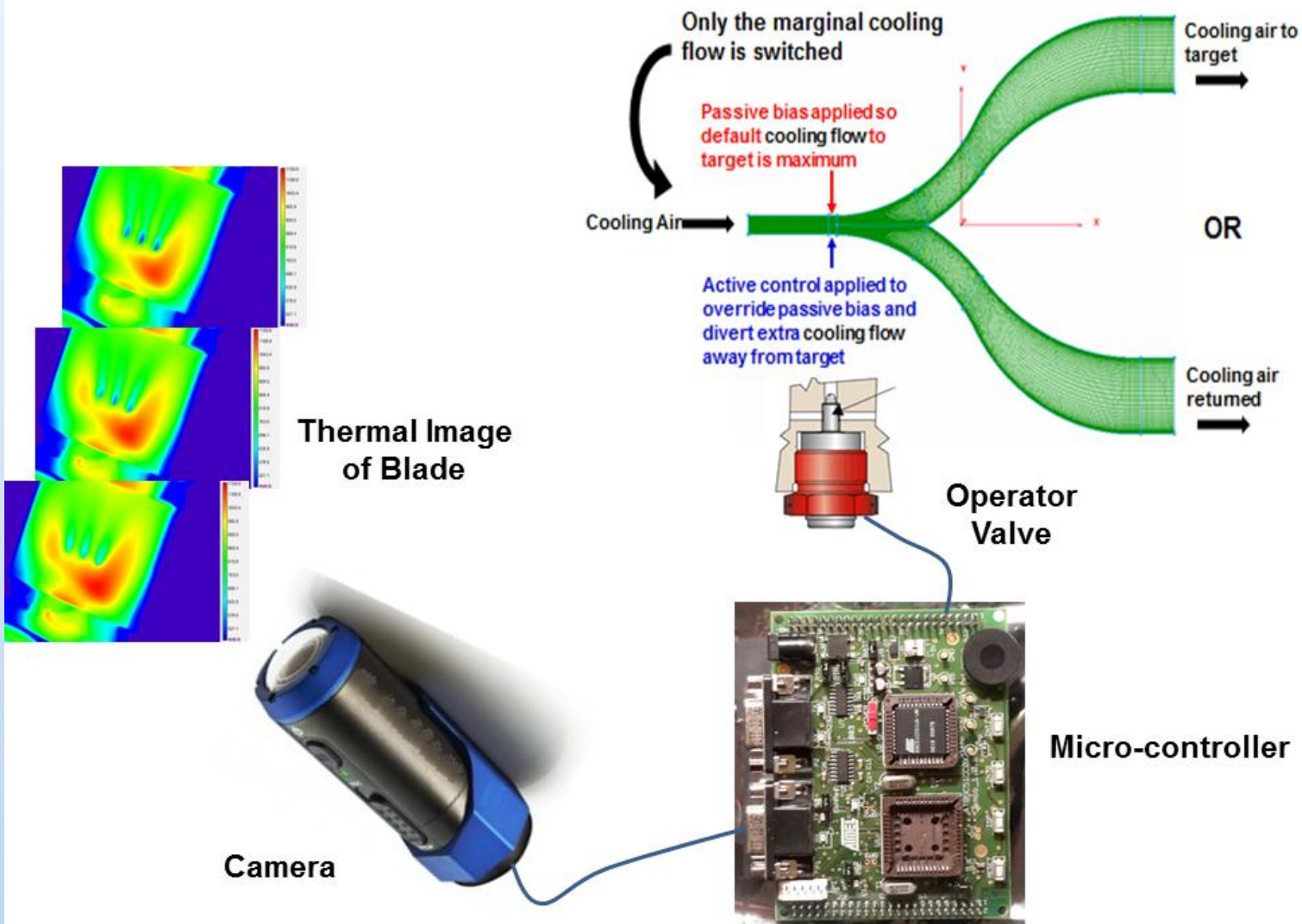
- 12% core flow used.
- If 5% saved, .8%SFC benefit.
- This translates to 1.5%fuel burn reduction.

» This was previous work for a 300 PAX aircraft
» Benefits might be slightly lower for N2A (767 class) aircraft

Approach

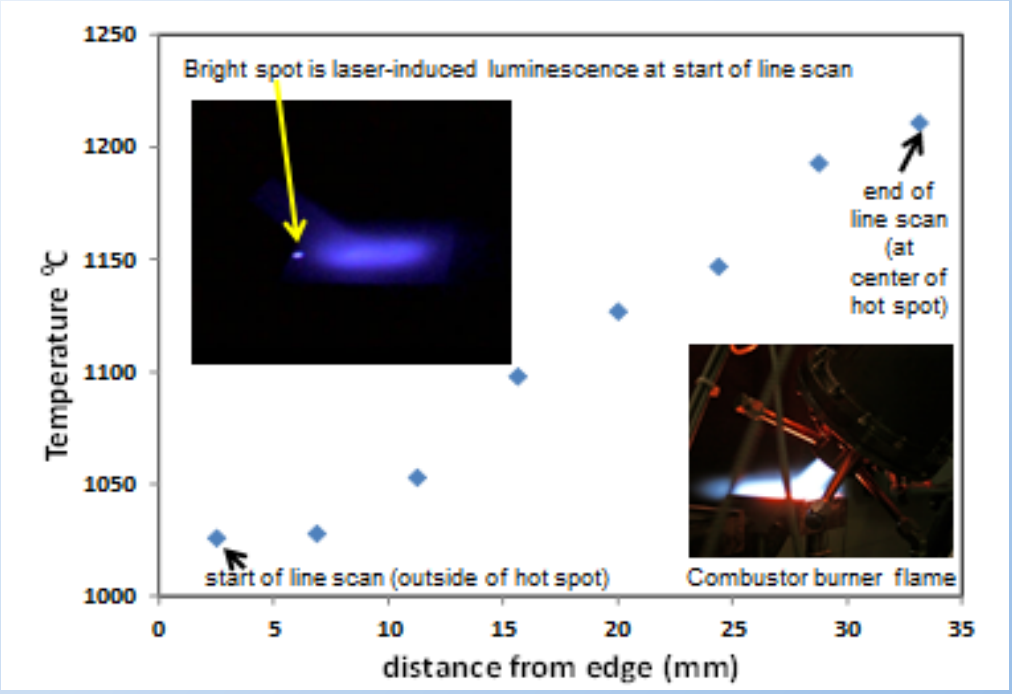
1. Real-time detection of thermal map on blade
2. Modular Cooling to target particular regions of blade/blade rows
3. Feedback loop to modulate cooling to cooling circuits defined in 2 based on real-time detection from 1.

Concept


Only the marginal cooling flow is switched
Passive bias applied so default cooling flow to target is maximum
Cooling Air
Active control applied to override passive bias and divert extra cooling flow away from target
Cooling air to target
OR
Cooling air returned
Thermal Image of Blade
Operator Valve
Micro-controller
Camera

Phosphorescence

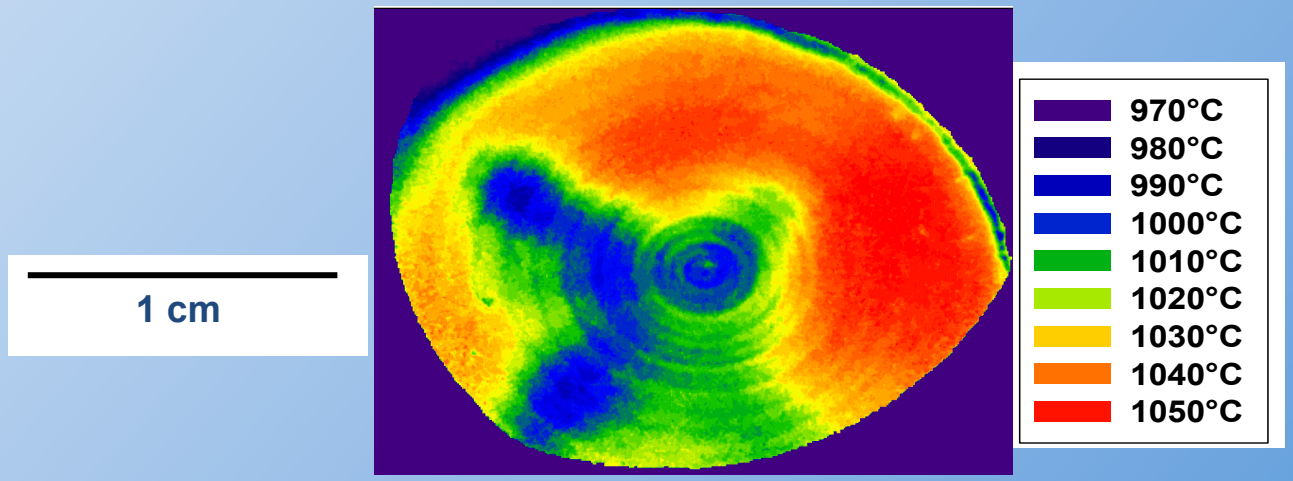
- Phosphorescence
  - Coupons with phosphor coatings to be developed and tested against existing methods (IR)



Phosphor Thermometry

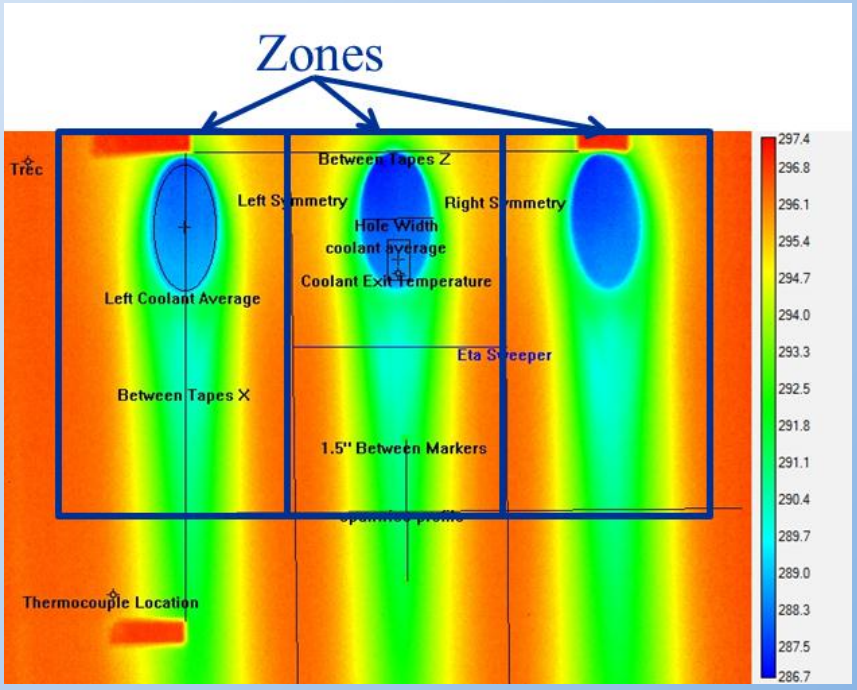
- Noncontact (unlike thermocouples)
- IR pyrometry has been problematic
  - Interference of radiation reflected by surface.
  - Temperature measurement averages over depth penetration of IR into ceramic thermal barrier coatings.
  - Uncertain emissivity introduces uncertainty into pyrometer measurements.
- Thermographic phosphors applied to thermal barrier coated surface overcome these issues.
  - Non-contact
  - No interference from reflected radiation
  - Insensitive to surface emissivity
  - Intrinsically surface sensitive

2D temperature map of cooling produced by air jet impingement



Infrared Thermography

- No need for laser beam
- Does not require syncing unlike phosphor method
- Noncontact method provides more detailed mapping of surface

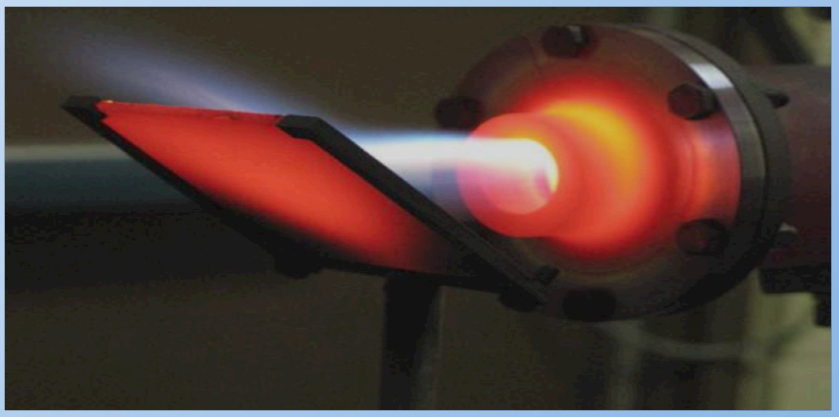


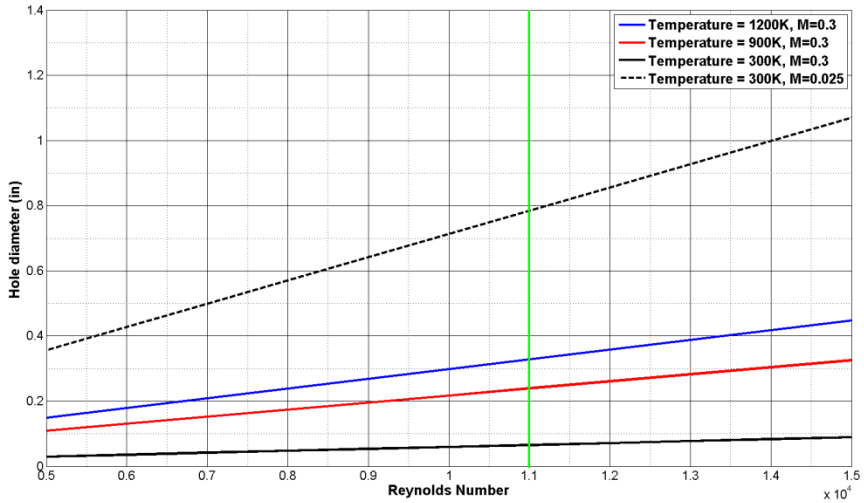
Hurdles

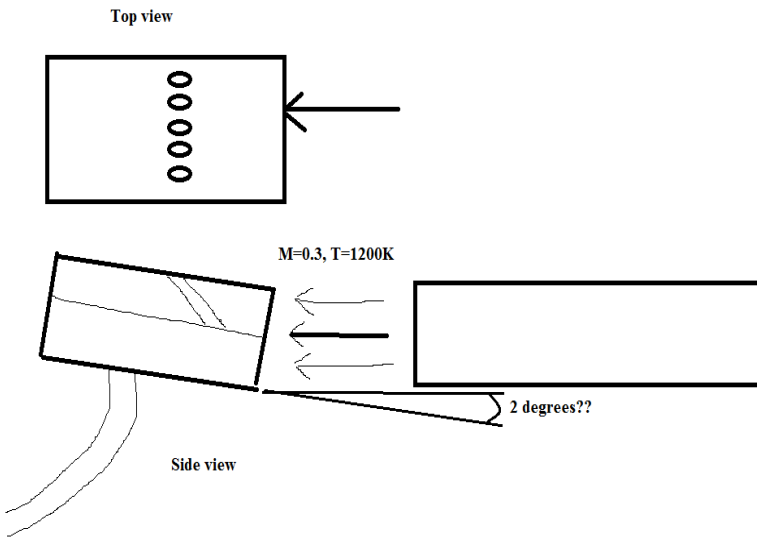
- **Resolution**
- **Precision**
- Processing speed
- Interface
- **Algorithm**
- Performance with degradation
- Optical access
- Operating environment
- Effect of environment on fluidic device operation
- Failsafe

Setup

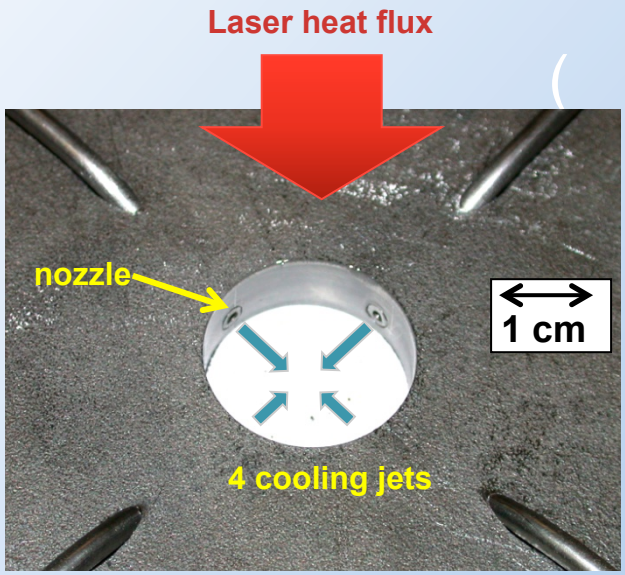
- 3” x 3” Plate
- T=1200K
- Diameter = 0.325in
- Hole spacing (pitch) = 0.975in
- Plate thickness = 1.25” ~8 diameters
- Holes at 30 degrees to the flat plate surface



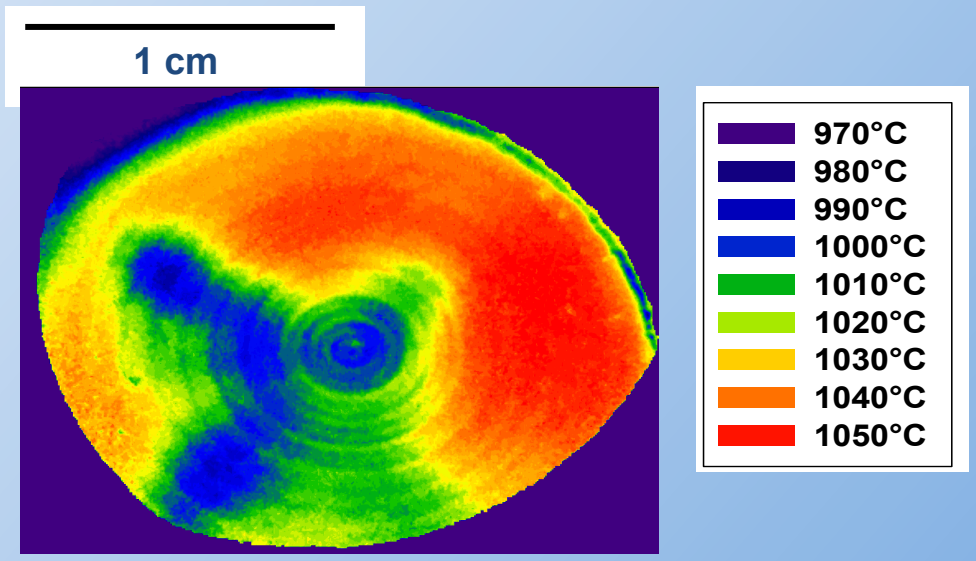




2D Temperature Mapping of Air Cooling Jet Impingement



Cooling air jet fixture in high heat flux laser facility



2D temperature map of cooling produced by air jet impingement

Insensitive to surface emissivity & reflected radiation!

Thermal Mapping of Honeywell Stator Vane in NASA GRC Mach 0.3 Burner Rig Flame

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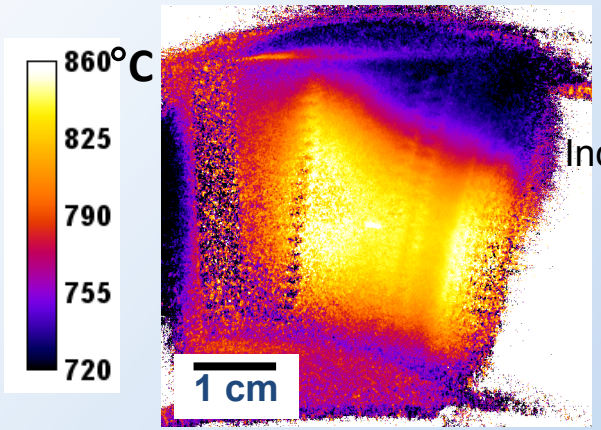
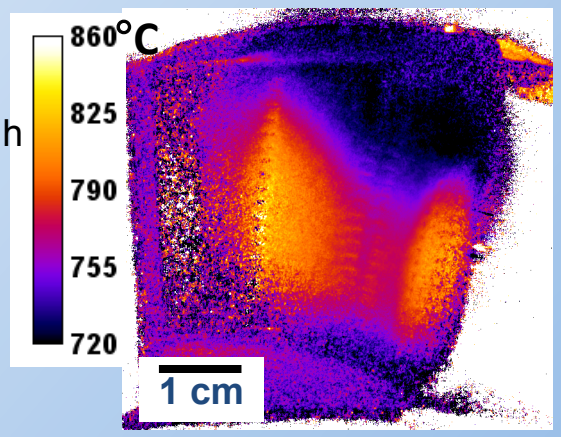
Surface temperature maps



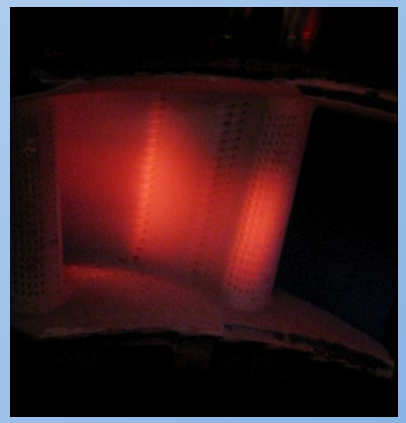
Min flow

Increase air flow through cooling holes



High flow

Visible



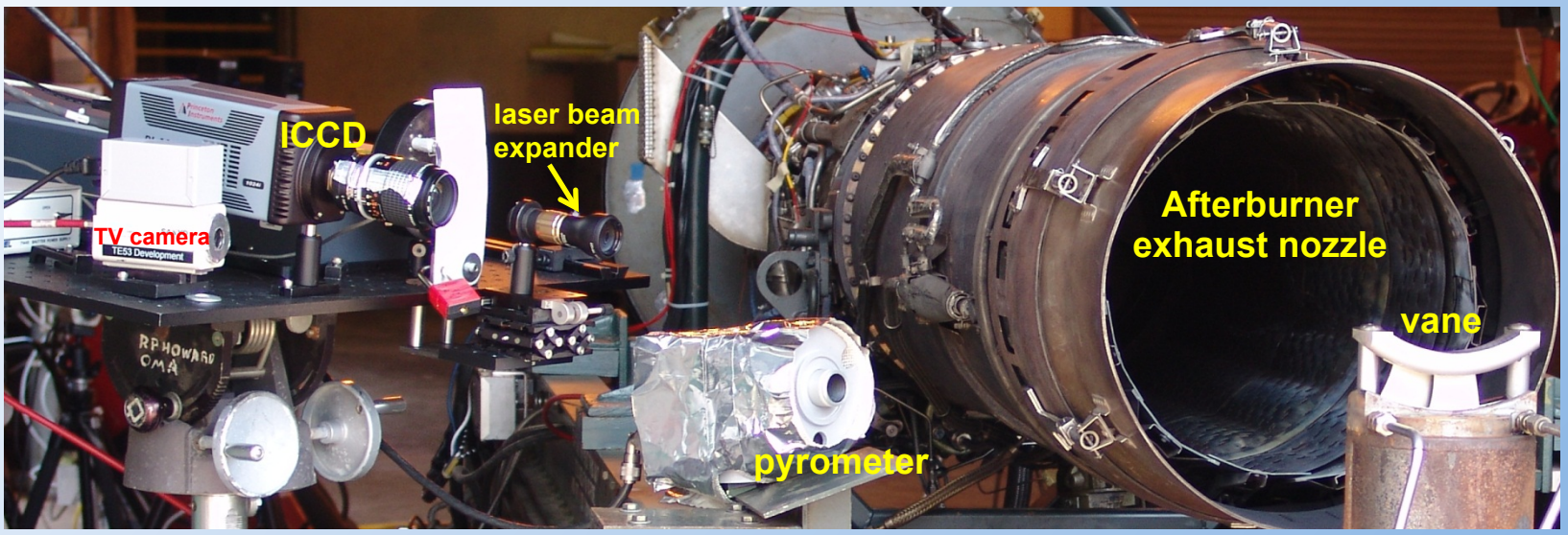
Good temperature measurements despite rust stain!
Would not be possible with pyrometer!

Before burner rig test

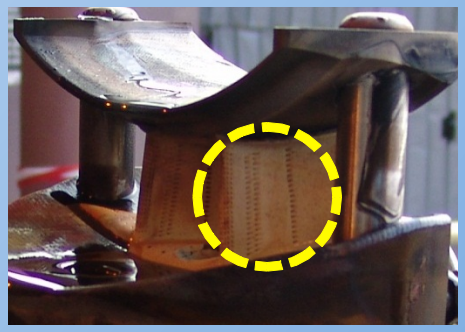
After burner rig test

J85-GE-5 Engine Test at UTSI
Broad, Uniform Heat Flux at Center of Flame

Surface Temperature Mapping Configuration



Afterburner Flame at Night



Expanded Laser Target

Surface Temperature Mapping of Honeywell Stator Vane in AEDC J85 Afterburner Flame

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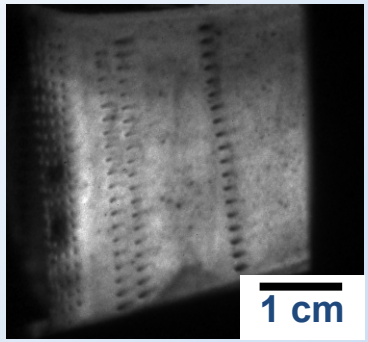
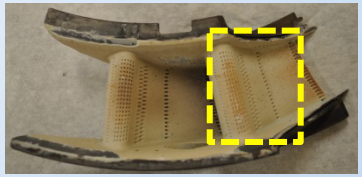
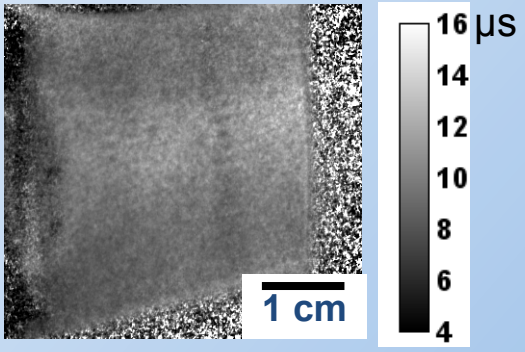
PLA (throttle) = 99°

First gate image

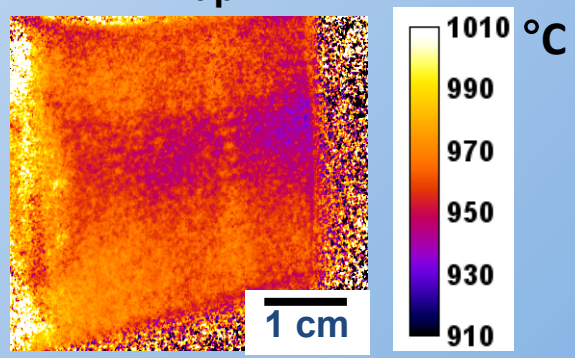




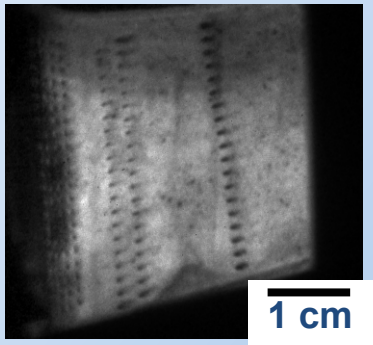
Decay Time Map

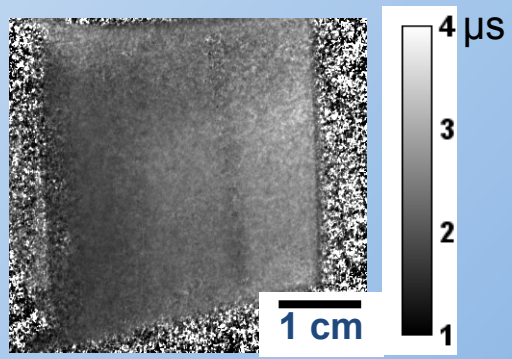


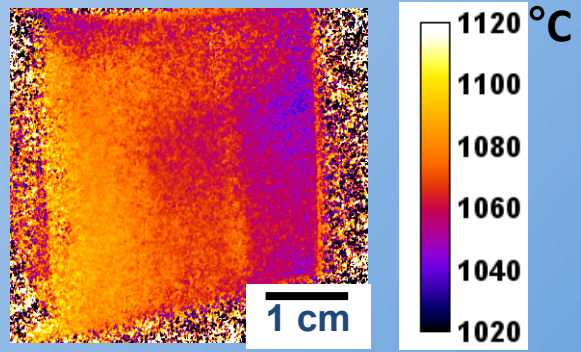
Surface Temperature Map



PLA (throttle) = 101°







Evidence of air film cooling

Phosphor Testing

- Testing delayed due to Alumina sample cracking and Burner Rig issues
- Estimate completion by April
- New materials selected to withstand machining and high temperatures

Infrared Thermography

- MATLAB script written to convert from pixels to coordinates.
- Hole detection method developed.
- Effectiveness calculation to be performed based on image values and not reference thermocouple.
- Surface is broken into zones.
- Each zone is compared to target effectiveness and produces a signal for the feedback mechanism of 0, 1 or 2.
- 0 means decrease coolant flow.
- 1 means increase coolant flow.
- 2 means system functioning, do nothing.

Infrared Thermography

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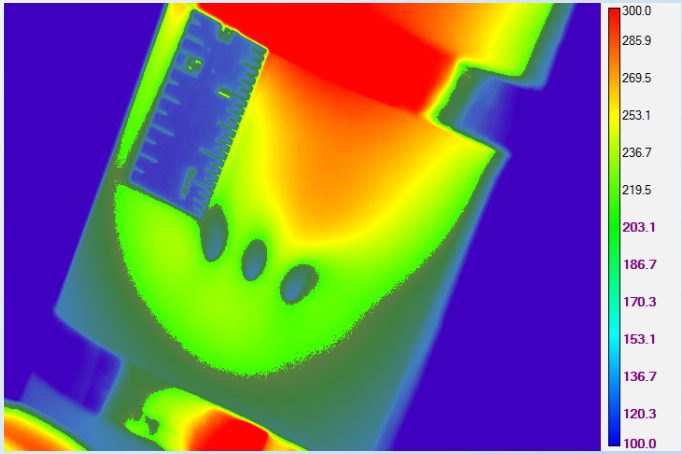
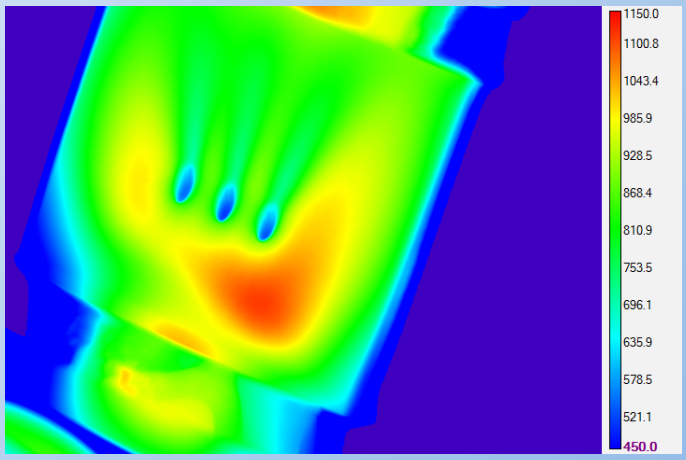
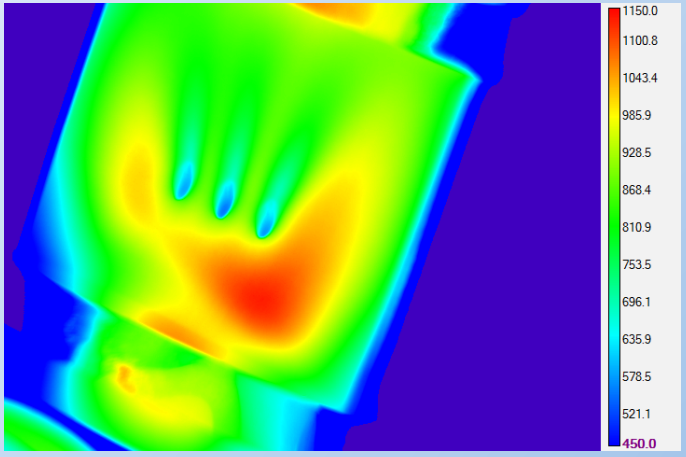


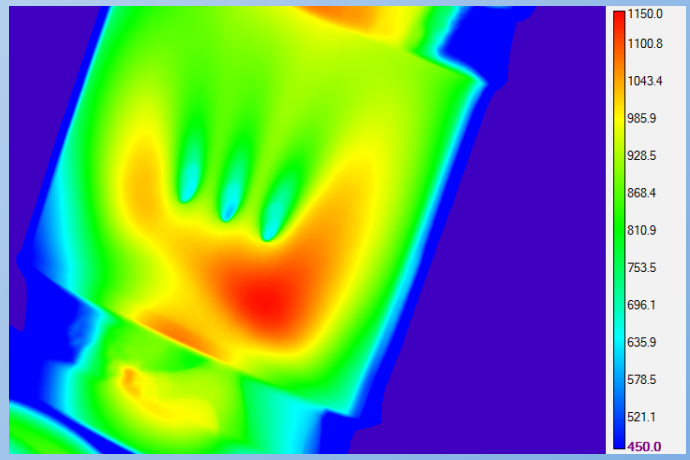
Reference measure



498 °C



510 °C



520 °C

Algorithm Example – 510C

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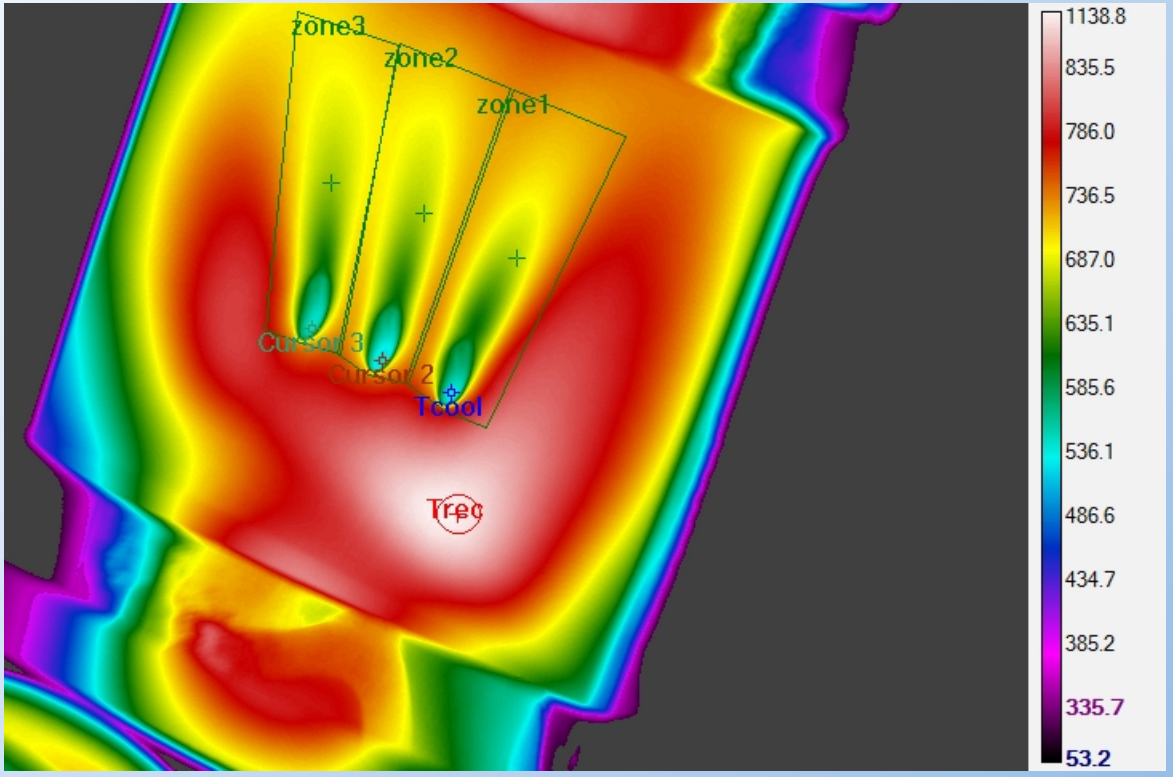

Target effectiveness = 0.5
Zone 1 mean = 0.519
Zone 2 mean = 0.57
Zone 3 mean = 0.57
Threshold T = 820K

Max T found in Zone 1 = 819K

Send signal 2 to controller Because Max T is close to threshold

Algorithm Example – 500C

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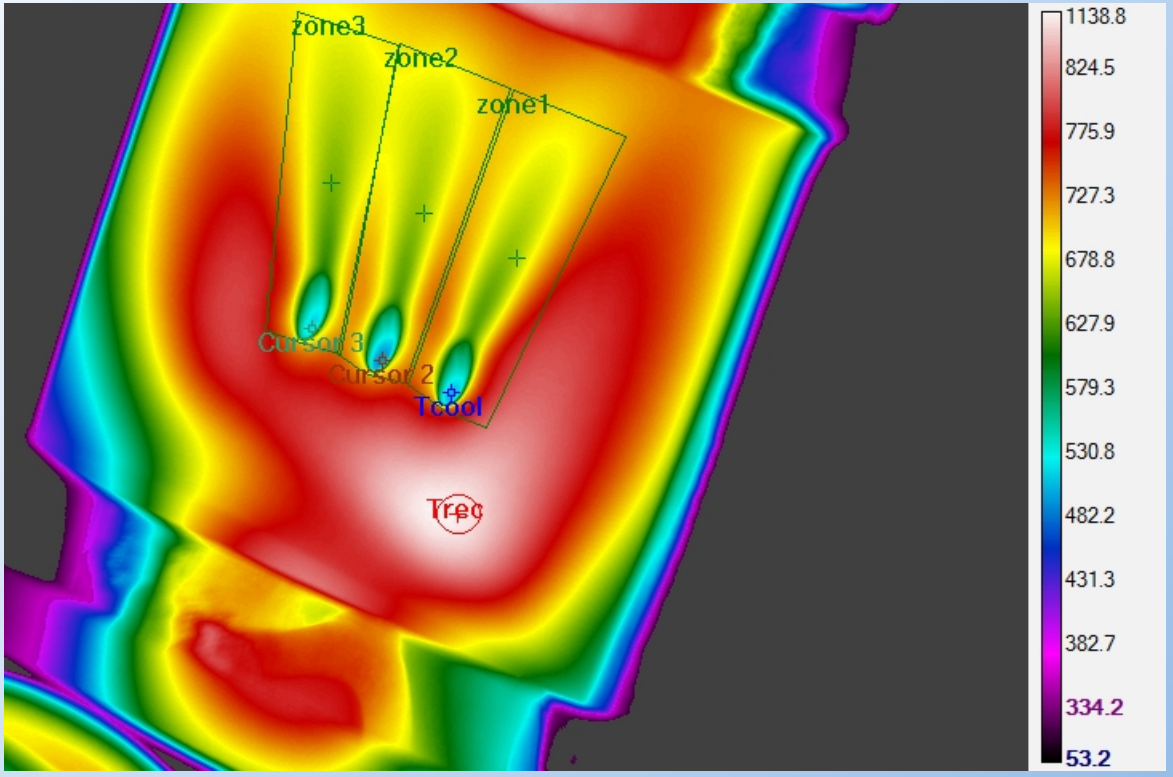

Target effectiveness = 0.5
Zone 1 mean = 0.485
Zone 2 mean = 0.53
Zone 3 mean = 0.53
Threshold T = 820K

Max T found in Zone 1 = 806.5K

Send signal 2 to controller – do nothing

Algorithm Example – 520C

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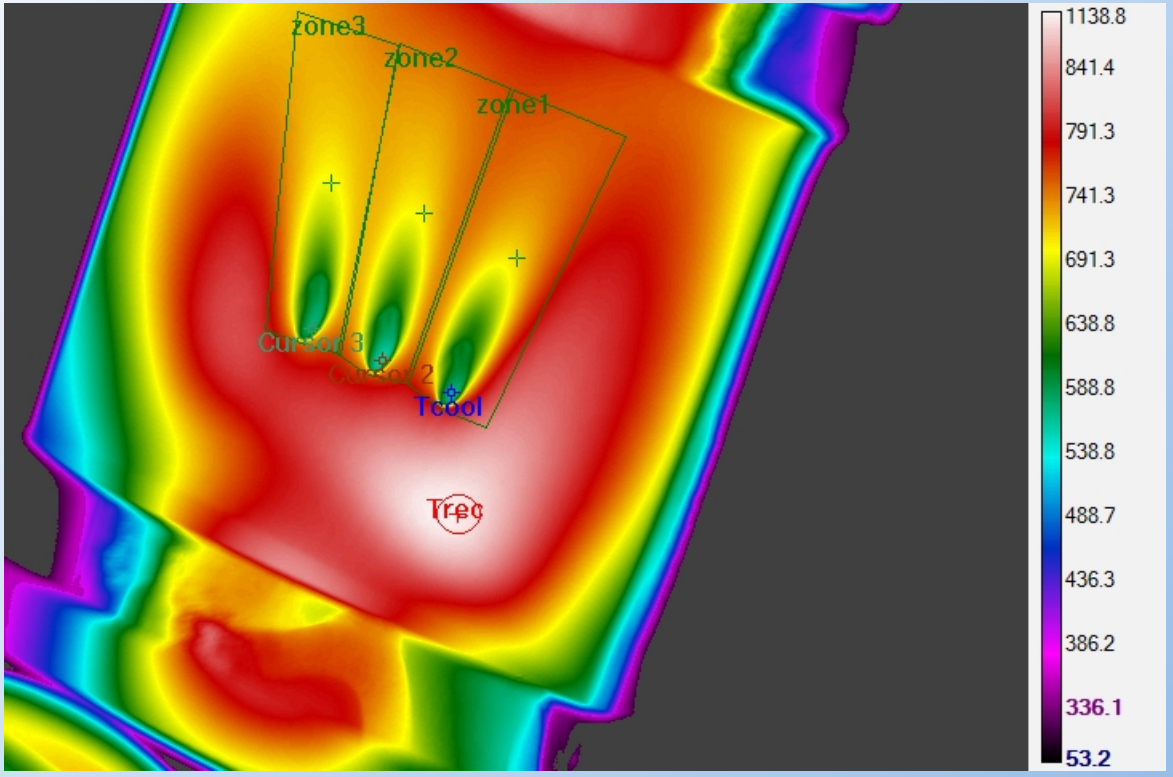

Target effectiveness = 0.5
Zone 1 mean = 0.509
Zone 2 mean = 0.56
Zone 3 mean = 0.57
Threshold T = 820K

Max T found in Zone 1 = 832K

Send signal 1 to controller – increase cooling because Max T is higher than threshold

Algorithm Regions

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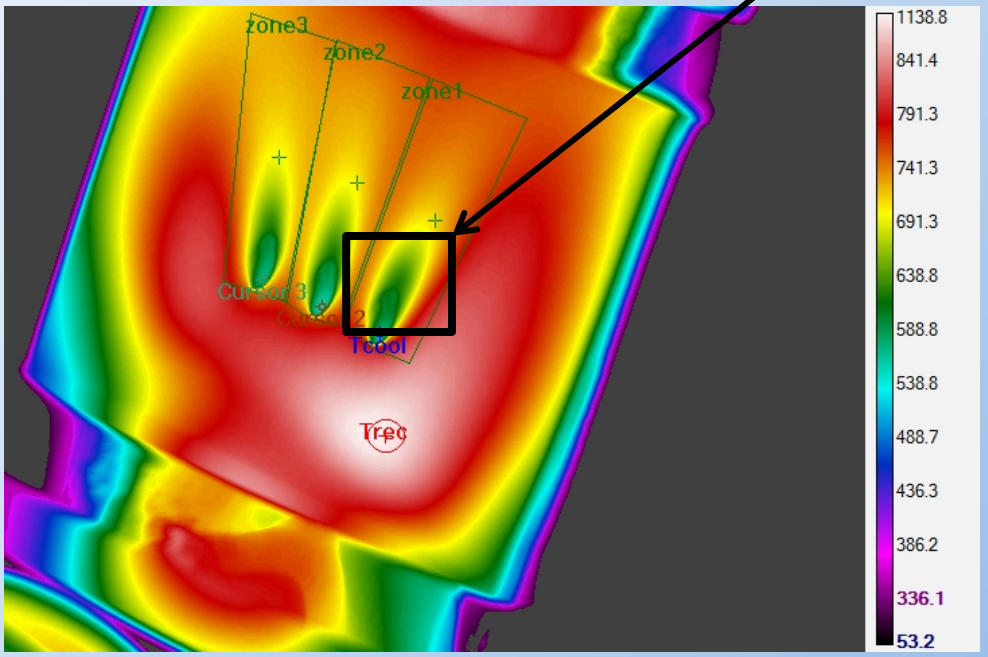
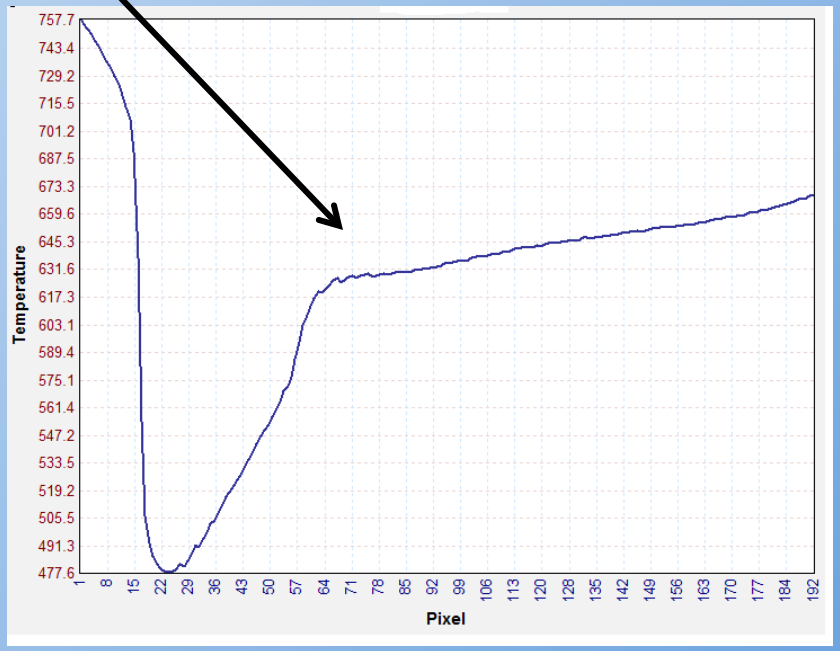
Cooling flow needs to be modulated based on whether blow off exists or not





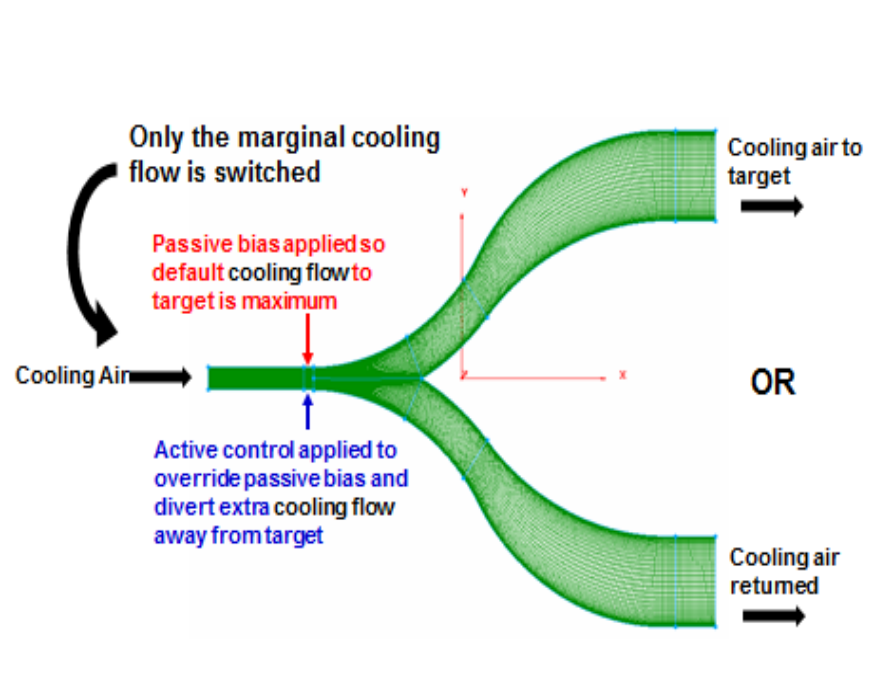
Modulation

- Modulation is to be achieved by controlling massflow of compressor core flow that is diverted to turbine.
- The massflow that is not required for cooling is allowed to continue to the combustor.
- Additional fine controls exist at the stage and blade level.
- The diverter can be controlled by a valve.
- This requires orders of magnitude less weight and space than a mechanical valve to control coolant.

Circuit Layout

- Cooling circuit to branch at
  - Compressor
  - Turbine
  - Blade Row
  - Blade

Determine feasibility



Cooling System

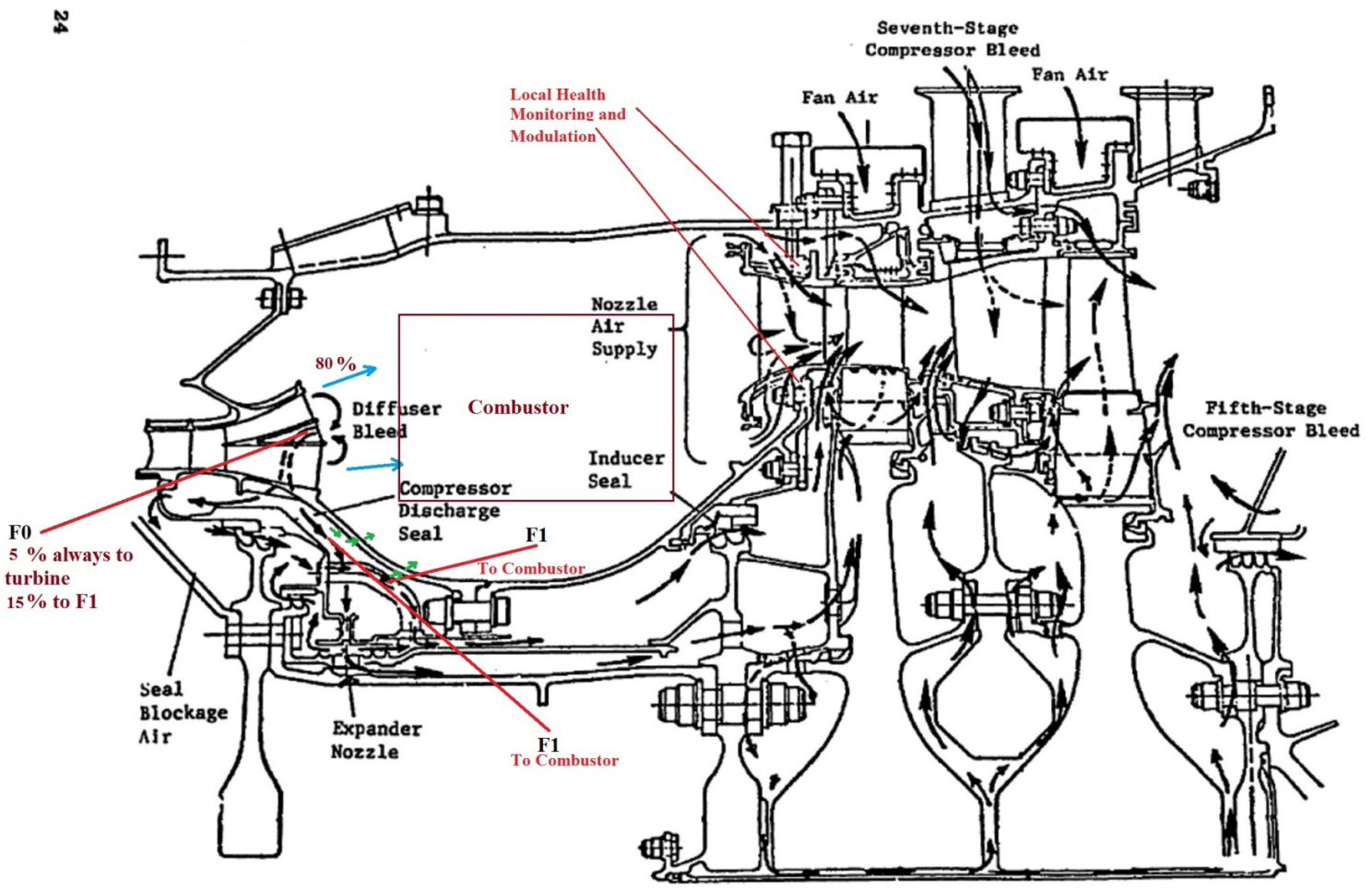


Figure 11. Rotor and Casing Cooling-Supply System.

Cooling System Cont.

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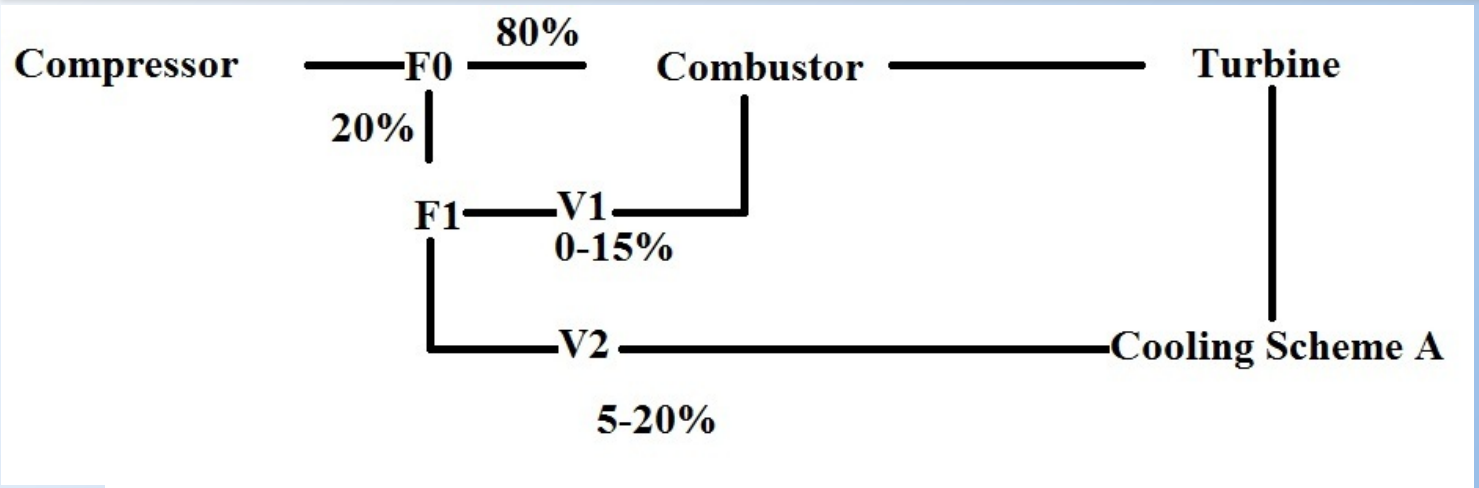
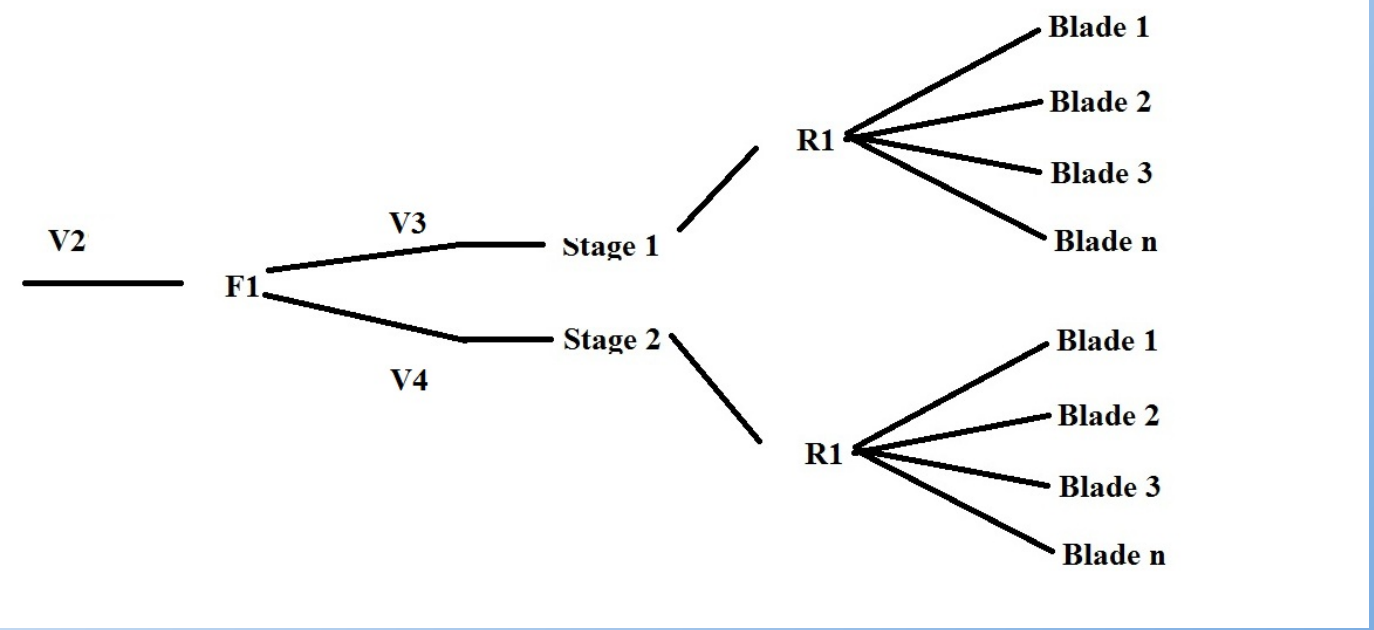
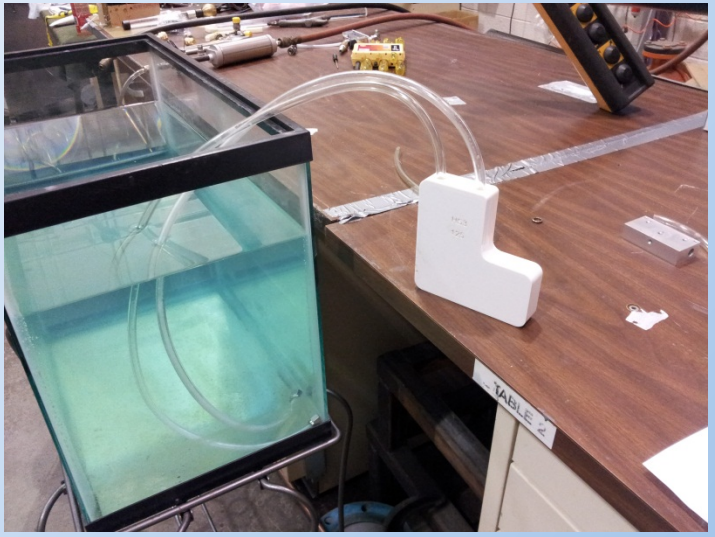
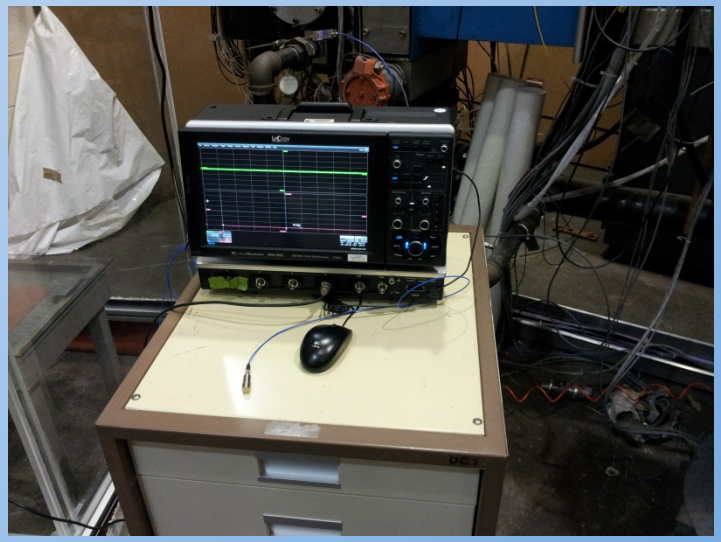




Fluidic devices

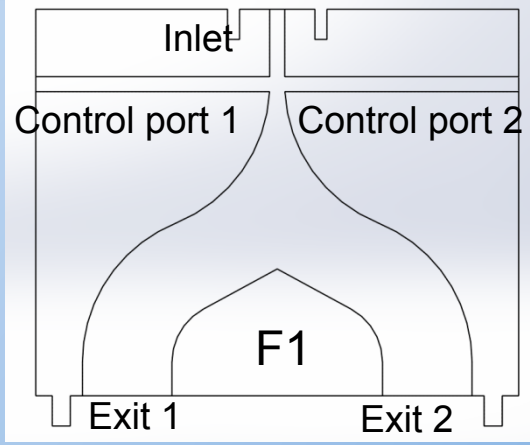
- A water tank used to enable pressure differences across exit orifices by varying exit tube depth in water.
- Demonstrated that by applying suitable pressure to control orifices, relative flow through exit tubes can be controlled.

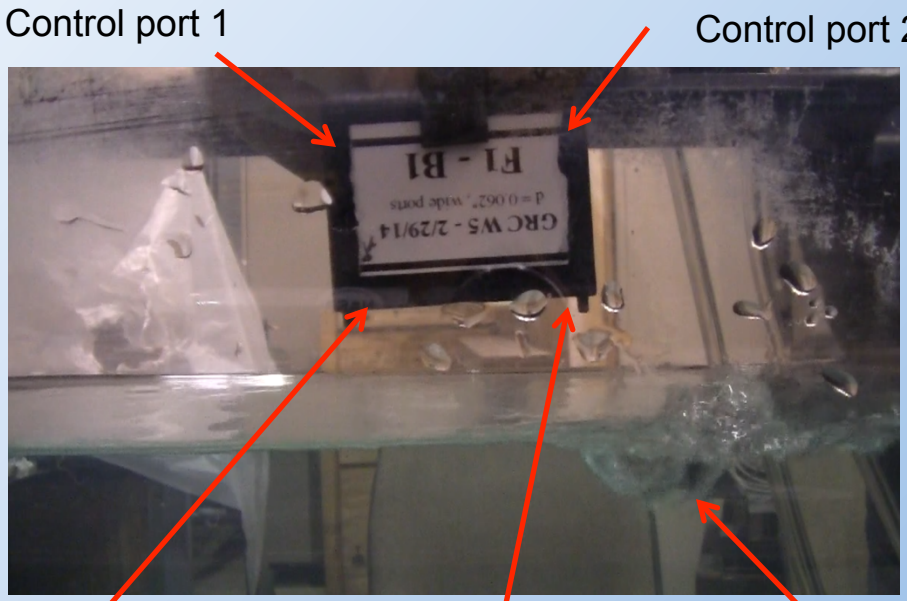


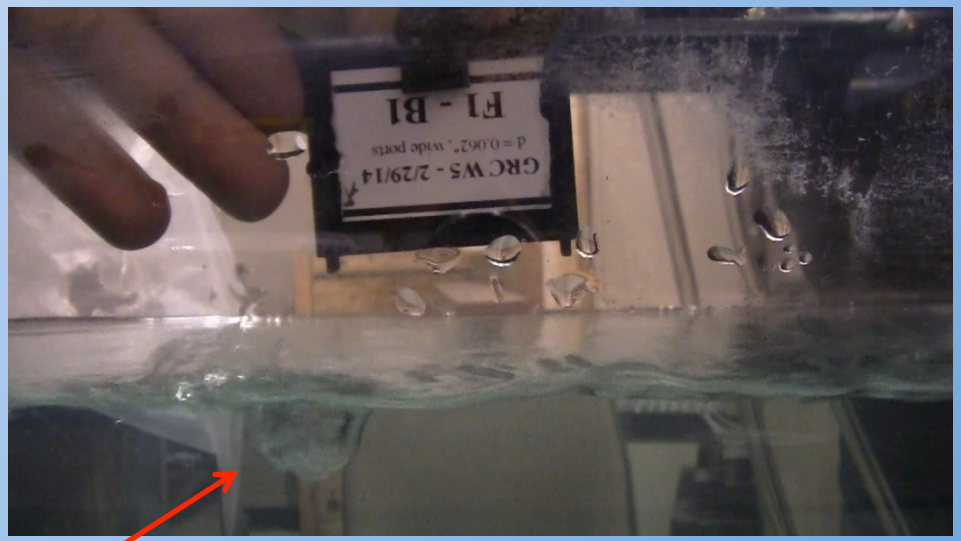


Fluidic Devices

- Showed that for F1, repeatable consistent control is possible
- If port 2 is closed, port 1 controls jet exit such that flow always exits at 2 unless port 1 is closed
- If ports are both open, both control ports can be used to switch flow







31

Conclusions

- Many tasks still in progress.
  - Burner rig phosphorescence tests
  - Prototype of sensing and feedback system
- Infrared thermography shows promise for on-board sensing.
- Fluidic devices are feasible as modulation mechanism.
- Space Act Agreement with GE in process to apply system concept to GE specific engine with flow rates and conditions specified.

Next Steps

- Testing of Phosphor thermometry in burner rig
  - Single beam vs. zonal scan
- Comparison with IR
- Test prototype controller with algorithm for test matrix to determine operating envelope
- Testing with engine scale hardware (optics, 3D geometry, smaller high temperature camera)
- Applicability under degradation of sample and optics
- Testing of interfaces between controller and sensing
- Long range goal would be to automate image processing via FPGA or embedded system.

Acknowledgements

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