Electro-Thermally Active Seal for Fast Response Tip Clearance Control

NASA LEARN Phase II Seminar

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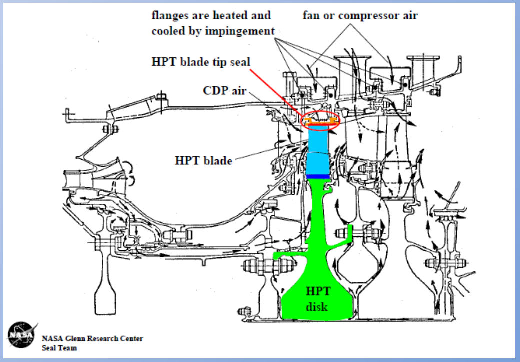
Outline

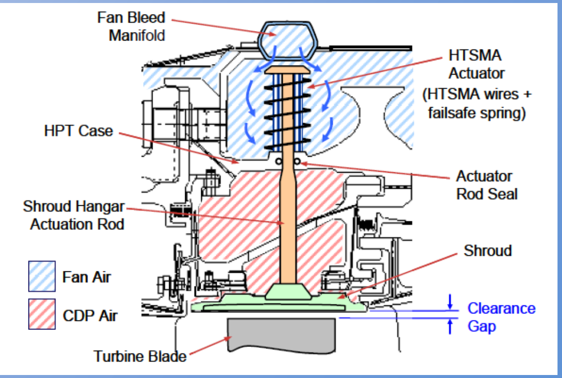
- Background
- Objectives
- System Approach and Requirement
- Actuator Designs and Down Select
- Integral Thermo-Fluid and Structural Modeling
- Fabrication Challenges
- Experimental Evaluation/Validation
- High Temperature Material Development
- Summary

Needs for Innovation

- Current State of Technology
  - Thermal expansion and contraction of entire shroud/case (Active Case Cooling (ACC))
  - Slow response and scheduled modulation
    - huge thermal mass with seal segments directly mounted on engine casing,
    - ineffective heating or cooling of the shroud via convection between shroud surfaces and air.
    - No asymmetry modulation



- Prior Research
  - Mechanical/Smart materials/Hydraulic/Pneumatic
  - External to engine case/shrouds and moving parts
  - Incompatibility with environment for HPT
- Need for Innovation
  - Fast Response Tip Clearance Modulation Mechanism
  - Light weight, compact and environmental compatible to HPT
  - Integral to shroud-case structure w/o moving parts



DeCastro, etc, 2005

Impact of Innovation

Fast Response Active Tip Clearance Control (FRACC)

- Enable turbine tip clearance set to "optimal" during longest flight segment (cruise)
- Reduce specific fuel consumption (SFC) and exhaust gas temperature (EGT)
  - 0.01" in turbine blade tip clearance equals:
    - 1 % in SFC
    - 10° C in EGT
- Low CO_2 emission
- More time on wing

Active Truss Tip Clearance Modulation

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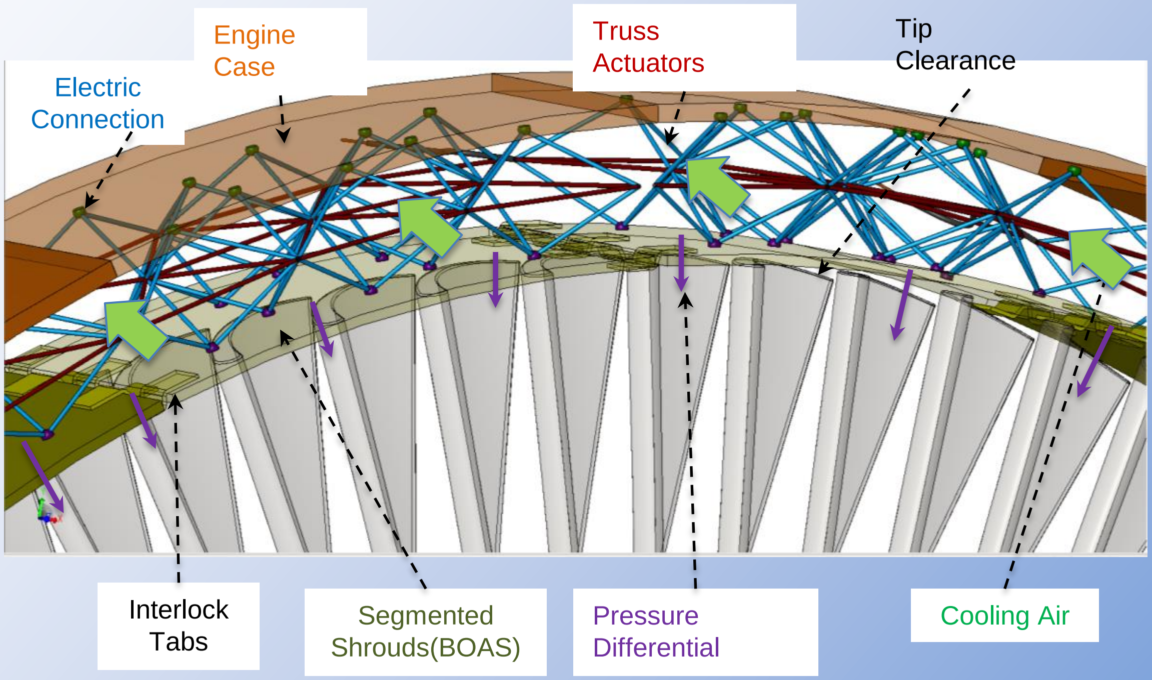
Concept of Fast Response Blade Tip Clearance Control



- Low thermal mass variable geometry truss for blade tip clearance modulation
- High temperature shape memory alloy (HTSMA) as primary actuation muscle
- Bleeding air cooling--one order of magnitude improvement over conventional ACC
- Light weight and Integral to engine case shroud structure
- Asymmetric and symmetry clearance modulation

No Technical Data subject to EAR or ITAR

Tip Clearance Actuation Requirement (1)

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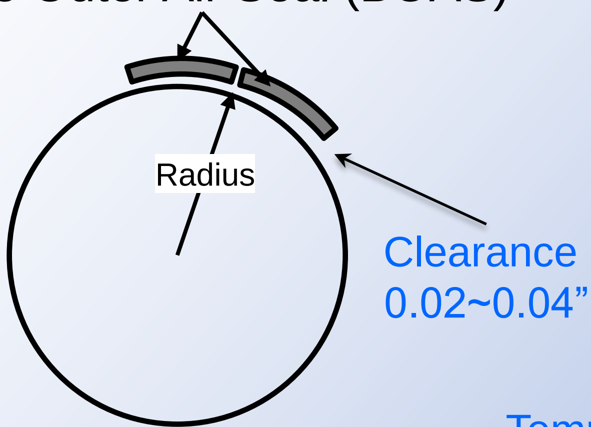
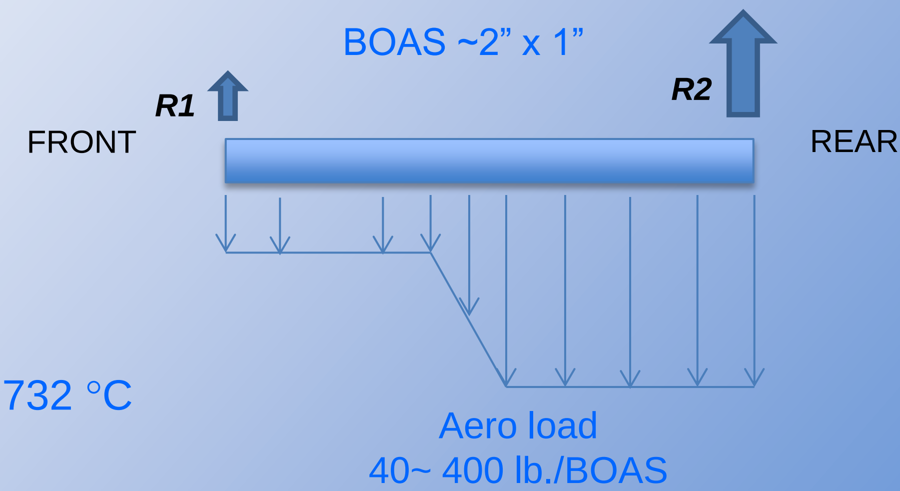
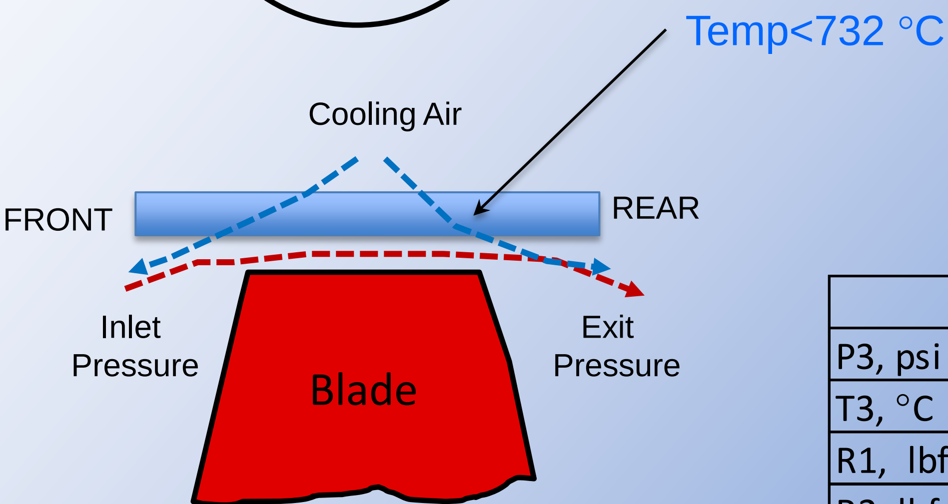
Blade Outer Air Seal (BOAS)







CROSS-SECTION VEIW

Notional Engine Design Conditions

	Idle	Take off	Cruise	Decent	Max
P3, psi	55	550	200	35	650
T3, °C	260	677	510	232	732
R1, lbf	14	143	52	9	169
R2, lbf	23	231	84	15	273

Tip Clearance Actuation Requirement (2)

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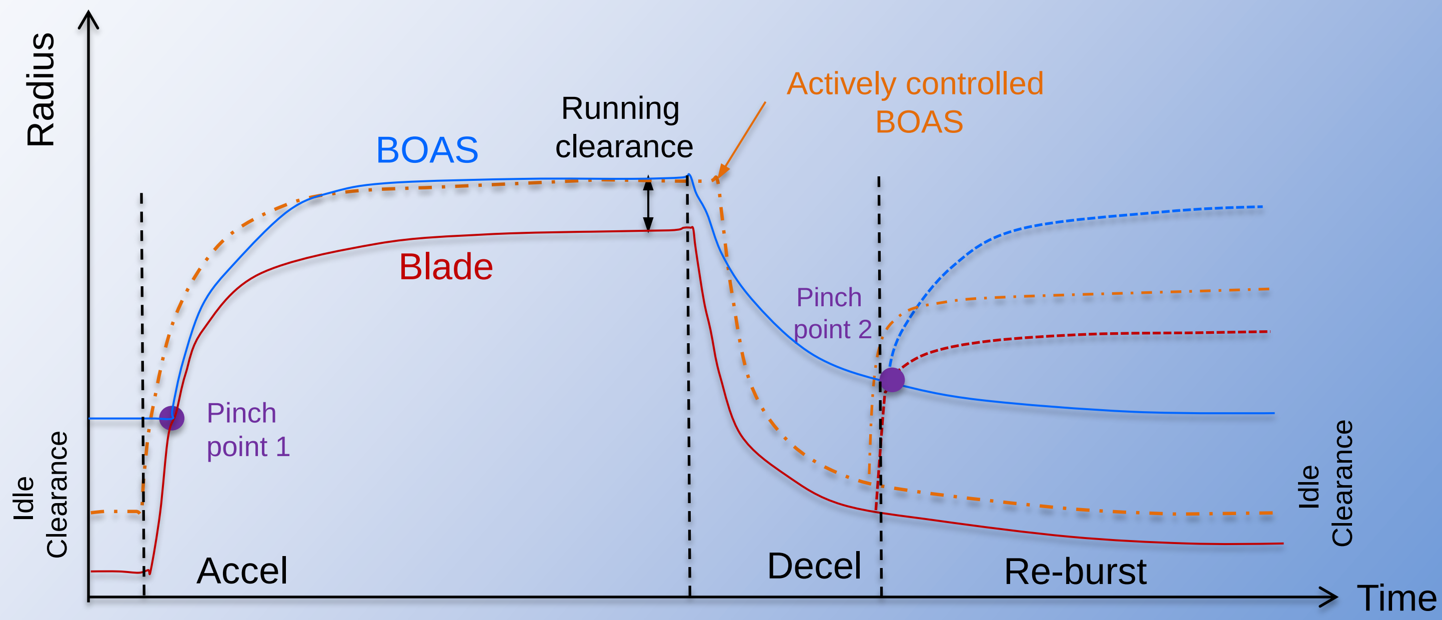

Concept Generation

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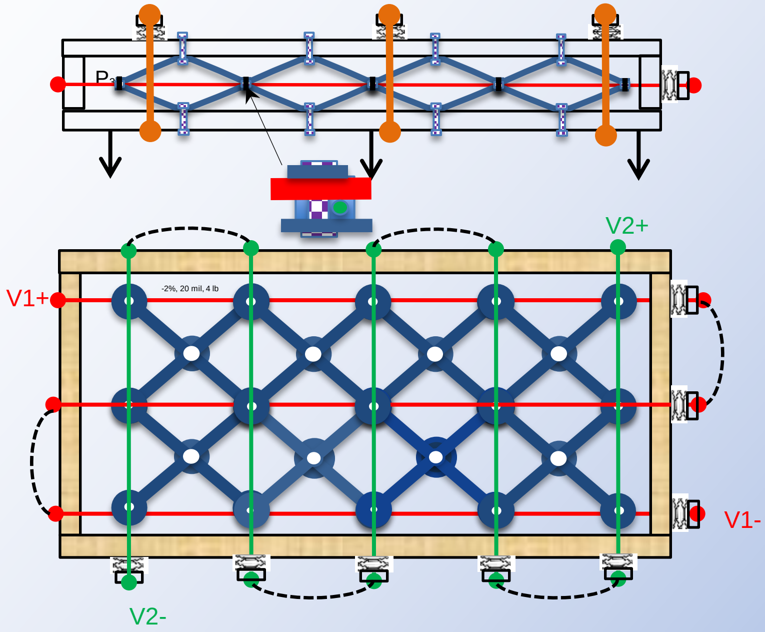

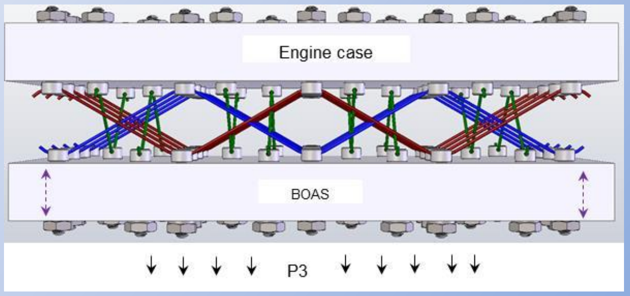

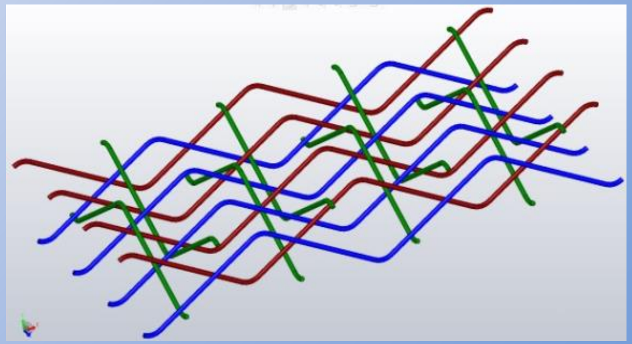

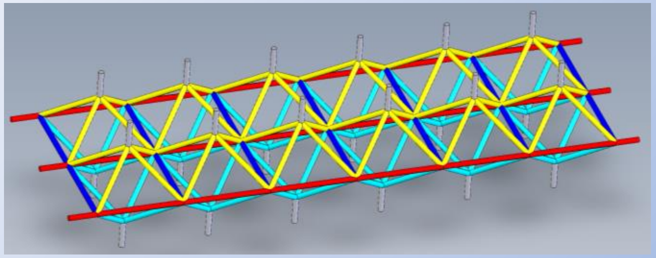

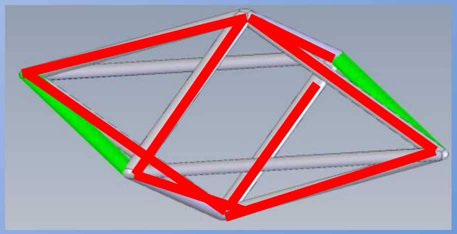

No Technical Data subject to EAR or ITAR

Actuation Down Select

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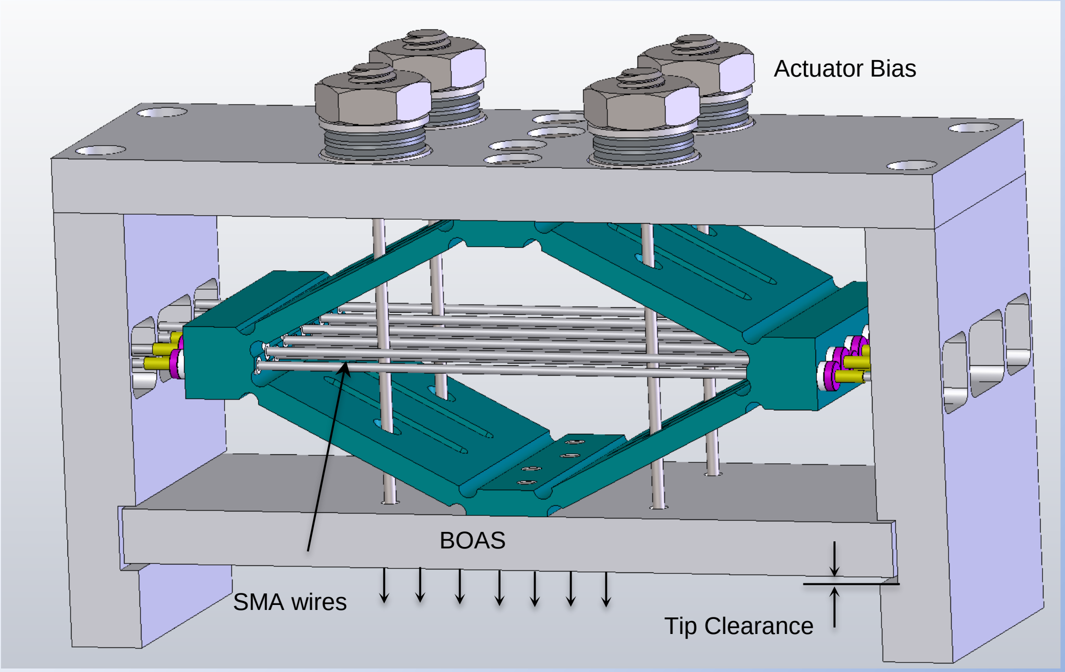

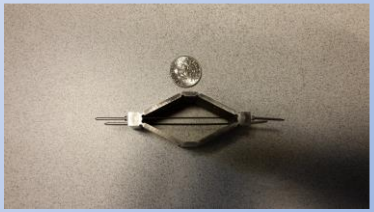

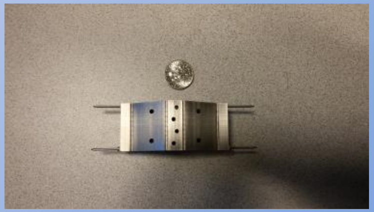

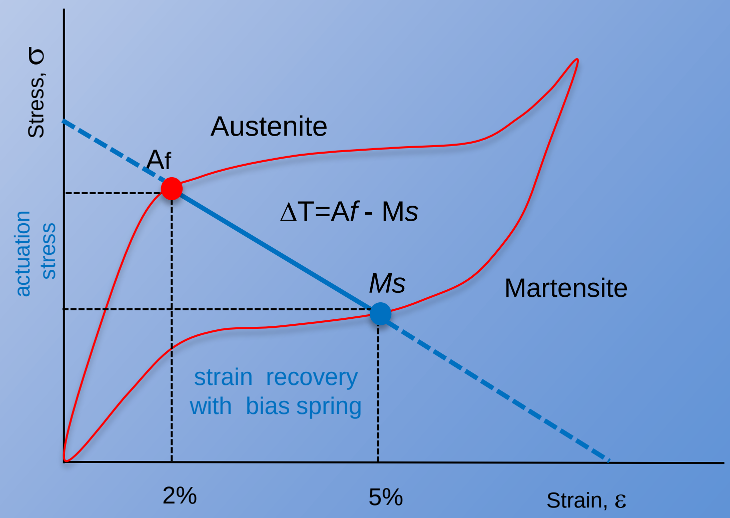

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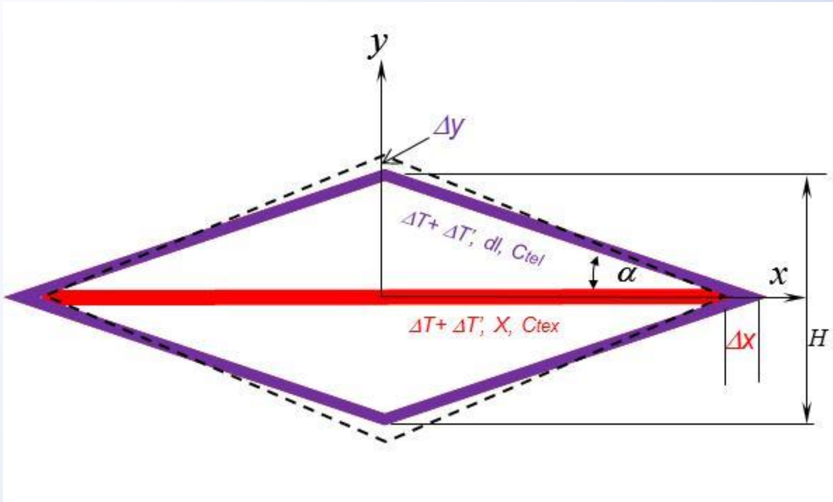
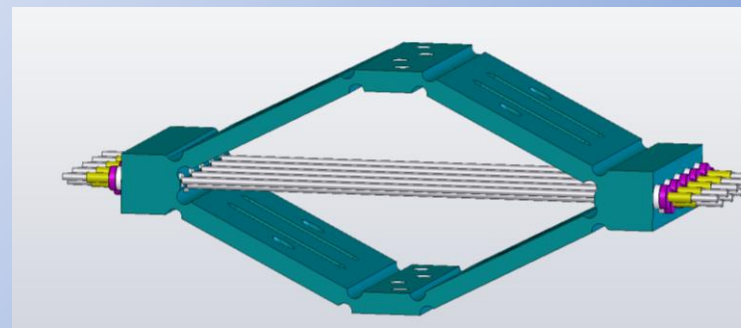
Actuation Design (1)





$$\Delta y = \frac{\Delta l}{\sin a} - \frac{\Delta x}{\tan a} = \frac{\mathbf{C}_{\mathbf{tel}}(\Delta T + \Delta T_l^{'})l}{\sin a} - \frac{\mathbf{C}_{\mathbf{tex}}(\Delta T + \Delta T_x^{'})x}{\tan a}$$

$$\cos^2\alpha = \mathbf{C}_{\mathbf{tel}} / \mathbf{C}_{\mathbf{tex}} \Rightarrow \Delta y = -\frac{\Delta x}{\tan a} = -\frac{\mathbf{C}_{\mathbf{Ttex}}\Delta T_x^{'} x}{\tan a} \Rightarrow \Delta H = -2\frac{(\Gamma(\Delta T_x^{'}) - \sigma / E_x)x}{\tan a}$$

- Motion conversion and amplification as function of angle α
- Environmental temperature immunity when thermal expansion matches

Actuation Design (2)

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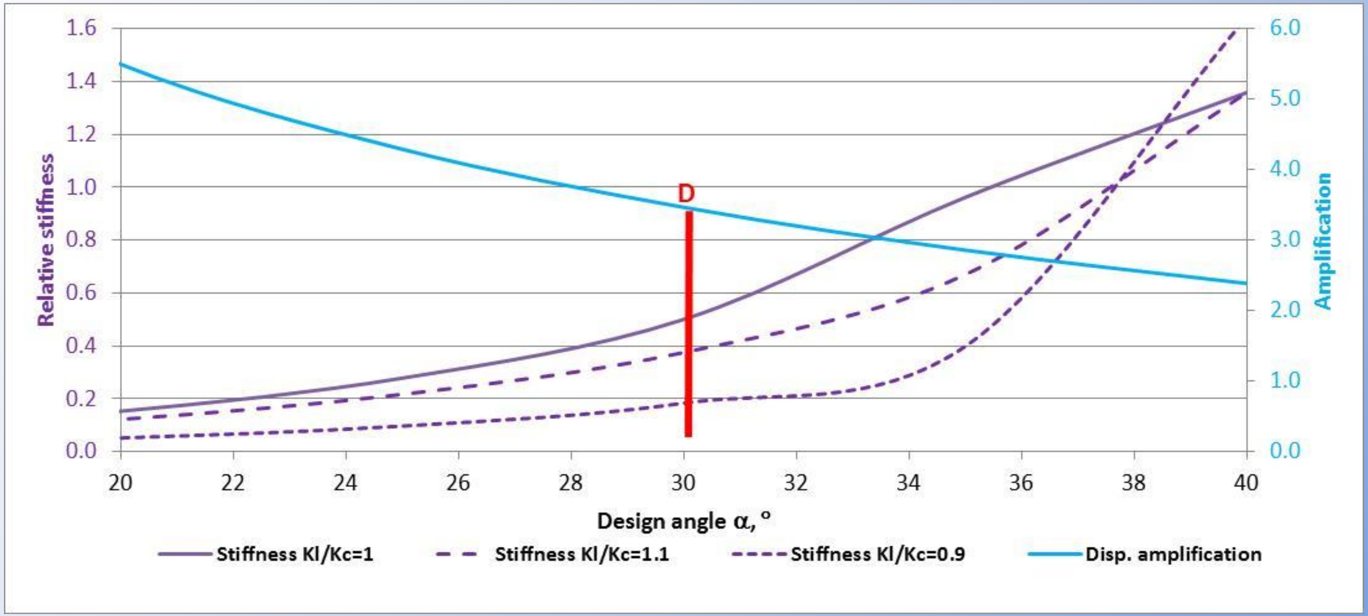
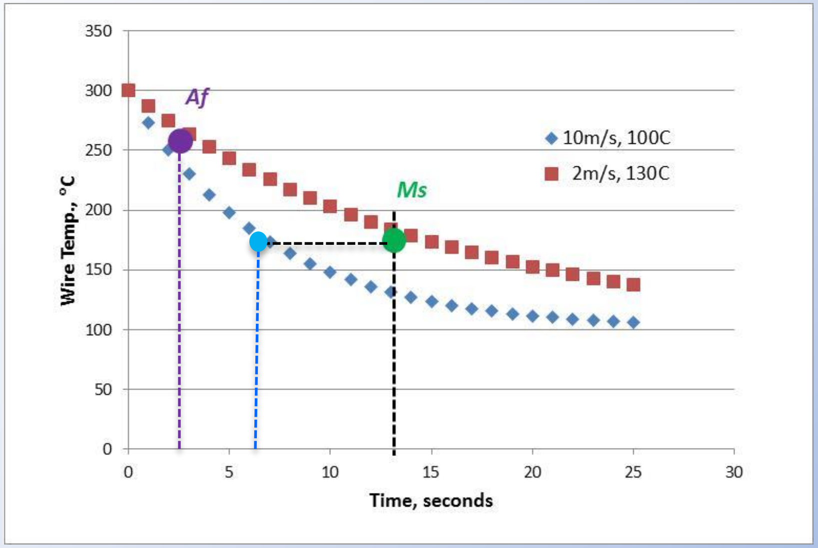


$$K_y = \frac{F_y}{2\Delta y_y} = -\frac{K_l K_x}{\dfrac{K_x}{\sin^2 \alpha} - \dfrac{2K_l}{\tan^2 a}}$$

- Finite stiffness as function of angle α
- Design is an optimization/compromise

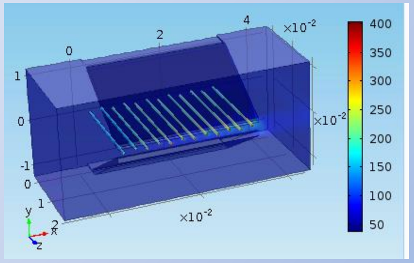
Integral Thermo-Fluid Mechanical Model

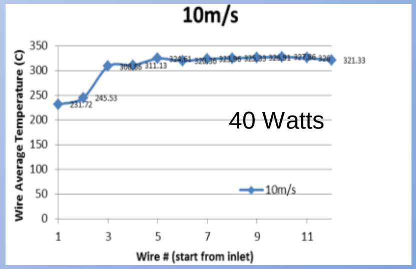
- Multi-physics coupled models in COMSOL
  - Electric resistive heating actuation
  - HPC bleed air cooling deactivation
  - Cooling air on all the time while power is on only during actuation

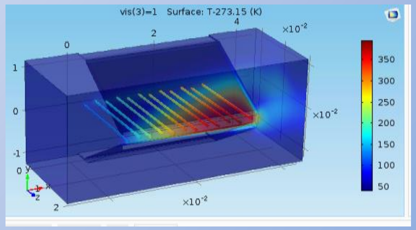


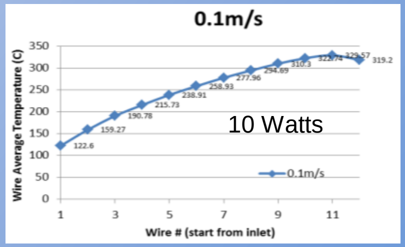
Air cooling with power off (widen clearance). Time =5~12s from *Af* to *Ms*

Contradiction: power vs wire temp uniformity

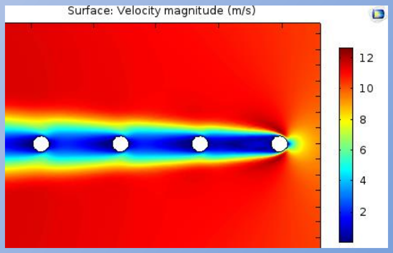


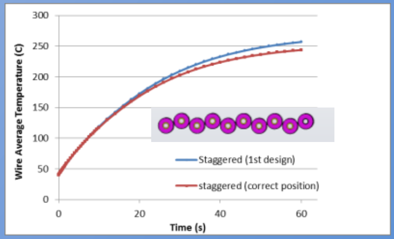






Resistive heating (activating) with airflow on





Temp. distribution and staggering effect

Integral Thermo-Fluid Mechanical Model

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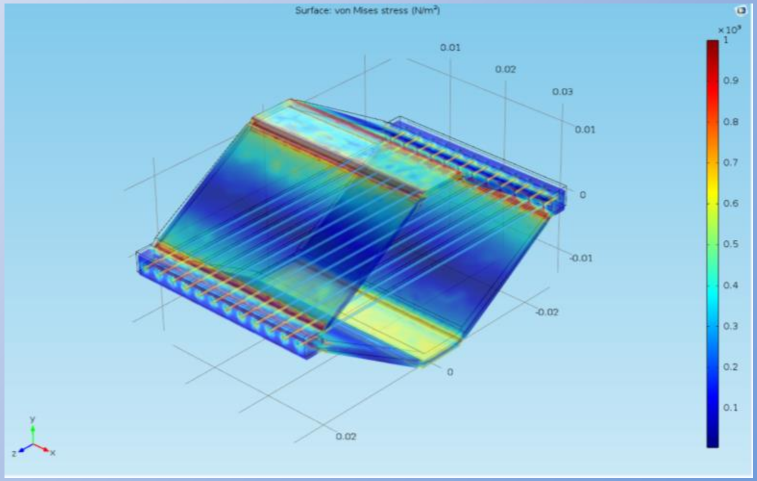
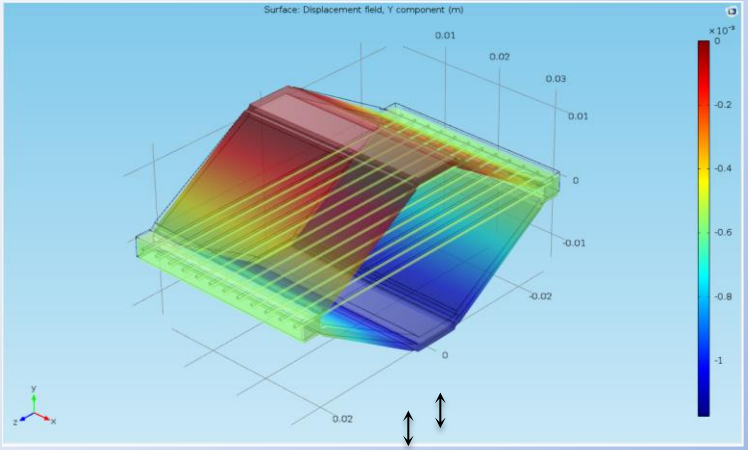
- Multi-physics structural models in COMSOL
  - Motion amplification (2x)
  - Aero load on BOAS reacted by spring bias
  - Fail safe with power supply

Structural response

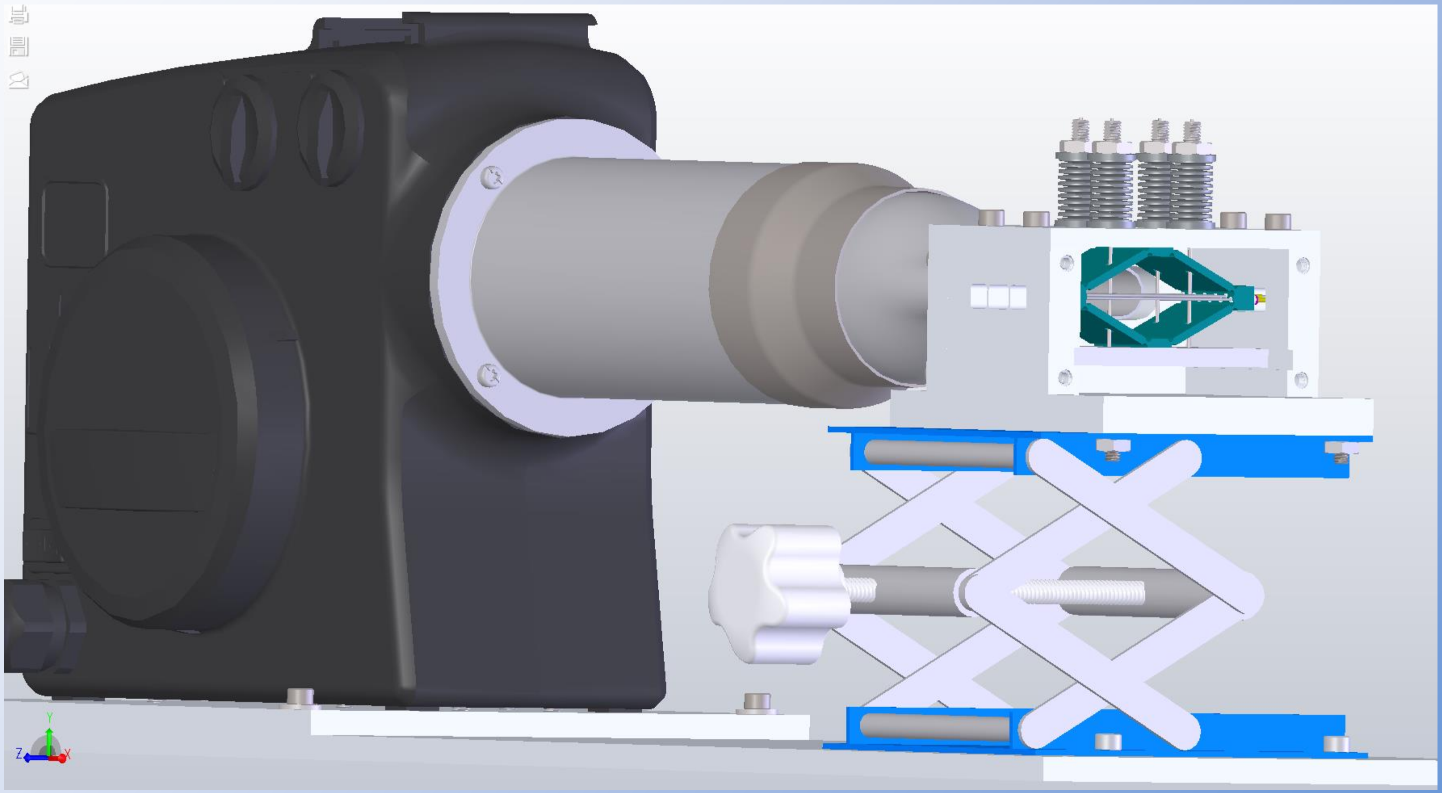


Full actuation against 150 pound aero load/ actuator



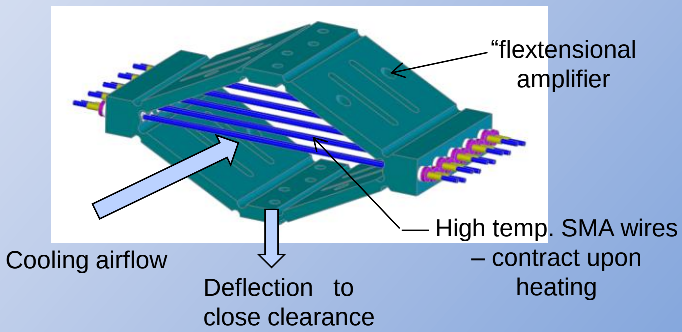
0.032 mils displacement

High Temperature Actuator Test Rig

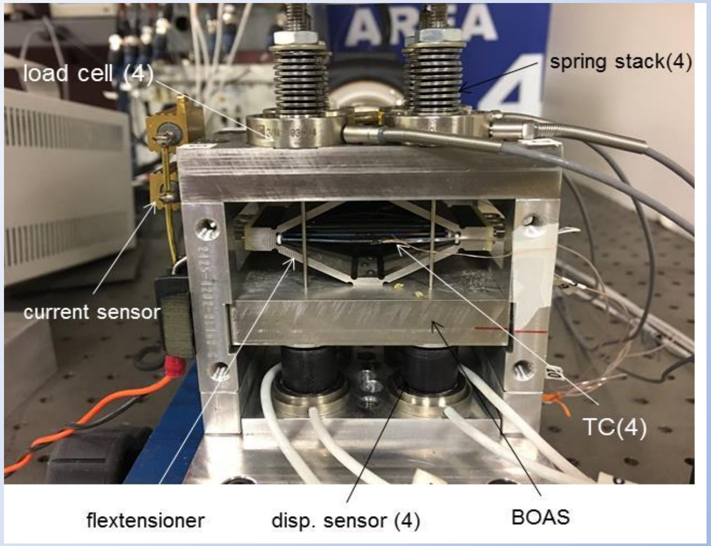


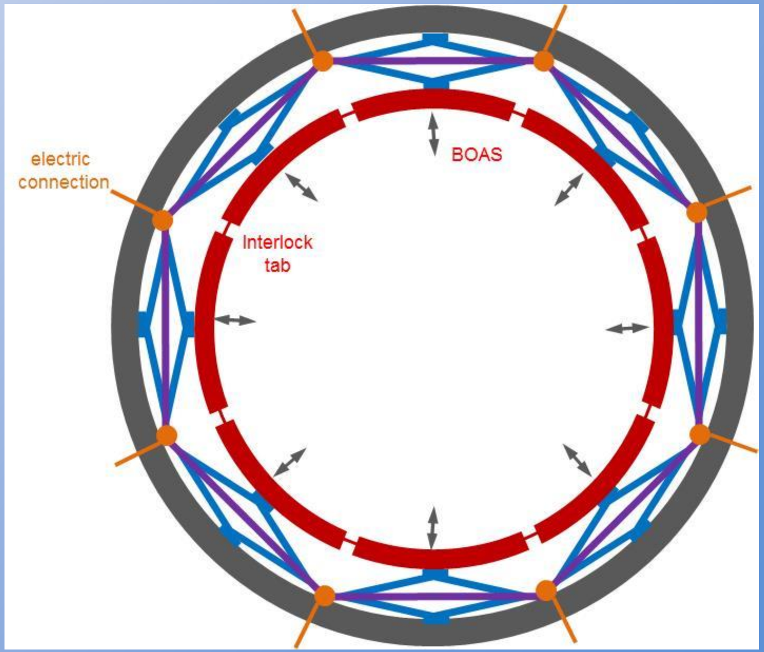
FRACC System Design & Prototype

- A Fast Response Active Clearance Control (FRACC) system has been designed, prototyped and characterized
- Based on state-of-the-art medium temperature (220°C) shape memory alloy (MTSMA) wire as primary muscle and 2D flextensional actuator.



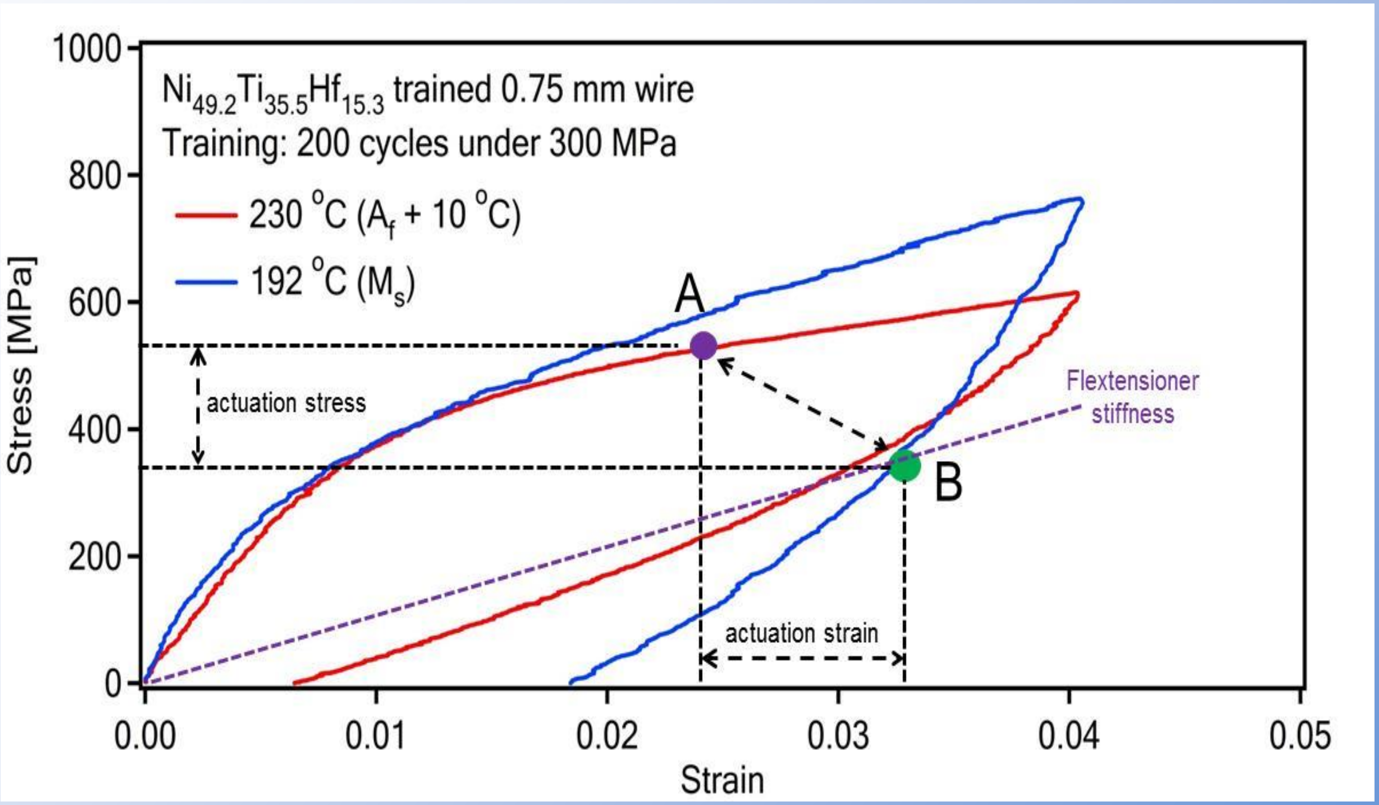
Core Actuator





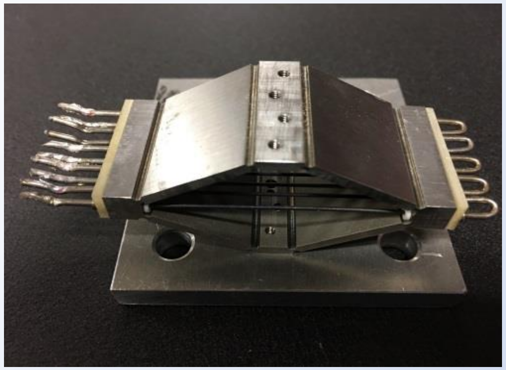
FRACC SIDE VIEW

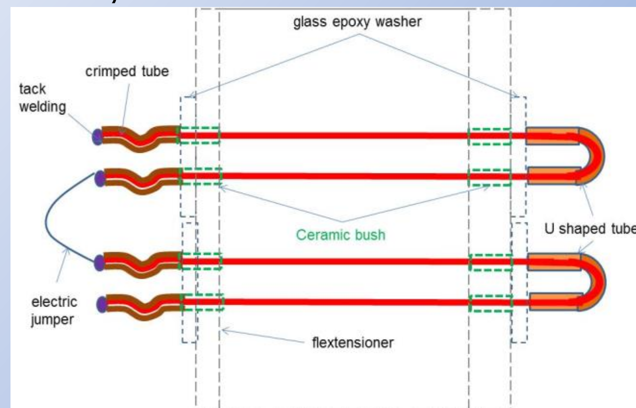
Medium Temperature Actuation Cycle



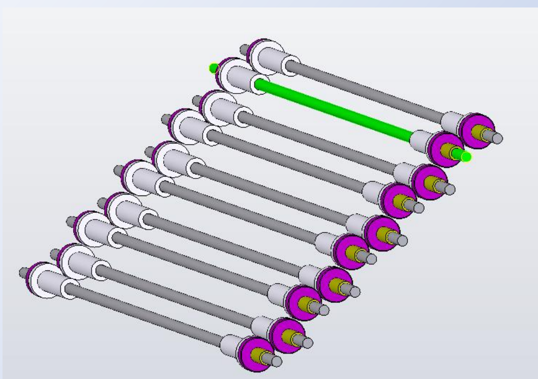
Fabrication and Challenges

Ti-Ni-Hf wire, diameter=0.75 mm

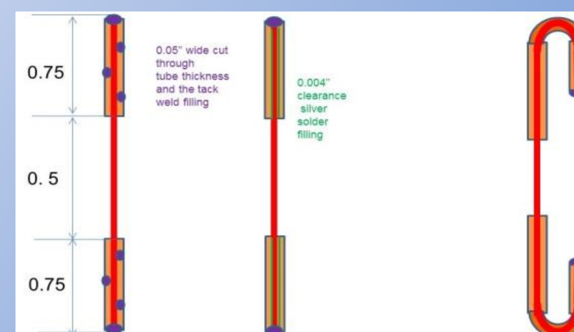




>50 Lb



Ceramic insulation bushes



<15-20 LB

Ti-Ni-Hf wire termination

No Technical Data subject to EAR or ITAR

FRACC Rig Test Results (1)

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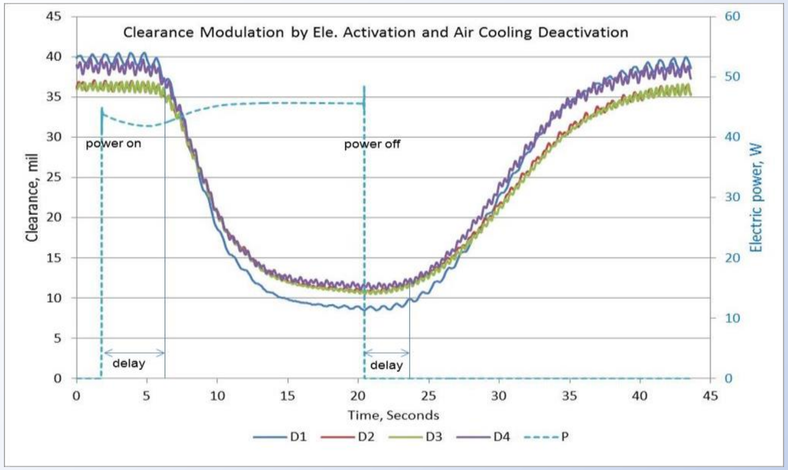

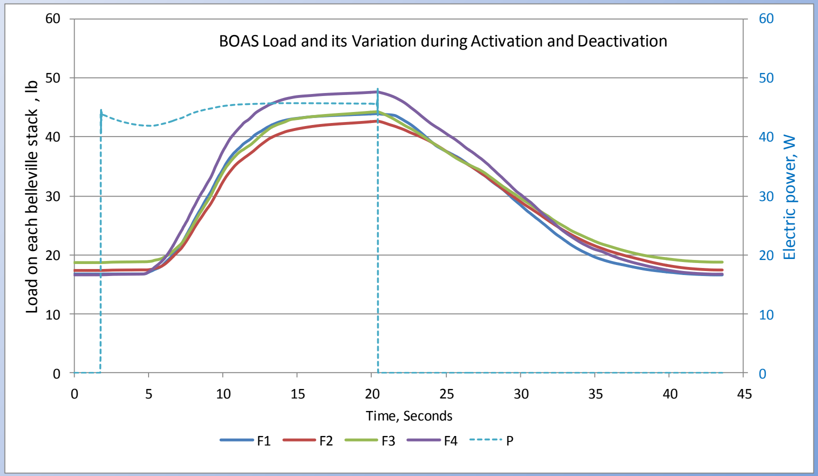

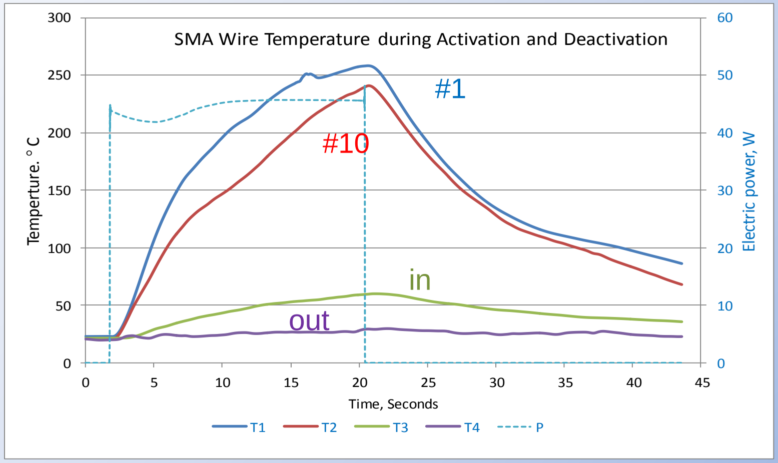

Room temp cooling air and very low airflow

- Test condition: 4 A, 21 °C air temperature and 0.1 m/s airflow
- Temperatures: wire #1 (T_1), wire # 10 (T_2), air inlet (T_3), air outlet (T_4)
- Clearance variation among BOAS corners < 10%
- Even wire temperature.

FRACC Rig Test Results (2)

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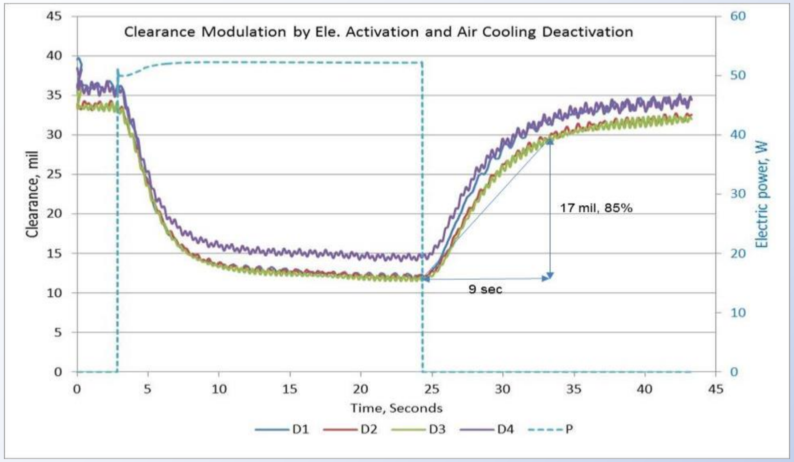

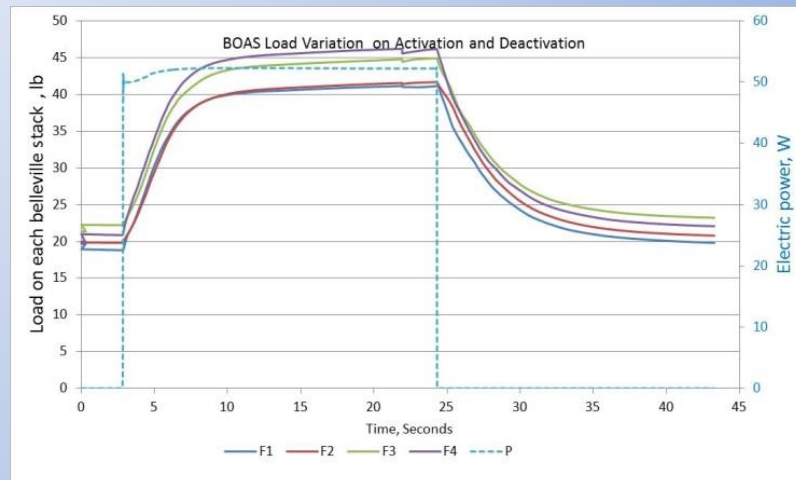

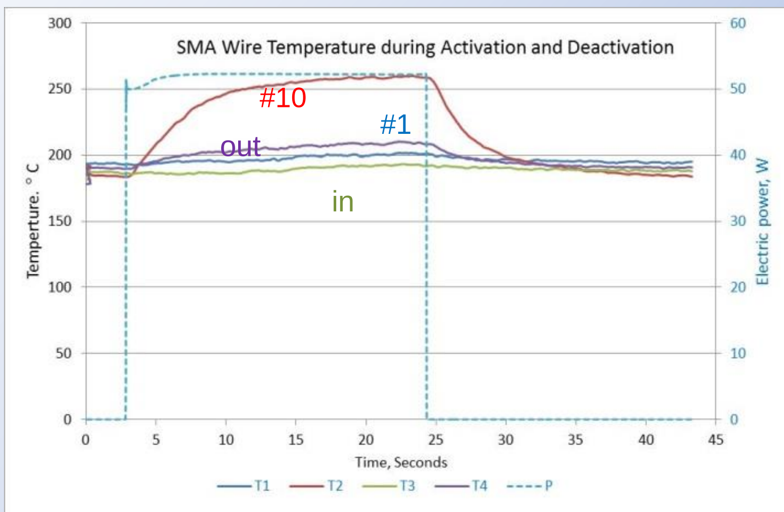

Elevated temp cooling air and high airflow

- Test conditions: 5 A, 180 °C ambient and 11 m/s airflow
- Temperatures: wire #1 (T_1), wire # 10 (T_2), air inlet (T_3), air outlet (T_4)
- Clearance variation among BOAS corners < 9%
- Uneven wire temperature (insufficient cooling at exit)

FRACC Rig Test Results (3)

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	Setting 1	Setting 2	Setting 3	Setting 4
Airflow, speed, m/s	0.1	2.32	4.64	11.13
Airflow. temp, °C (normial)	21	130	170	180
Electric power, Watts	42	44	51	53
Bias load, lb	75	80	79	82
Tip clearance change , mil Analytical	25~30 52	23~25	22~23	21~23
Max load, lb, total/range	168/42~4 5	170/43~46	172/42~43	178/42~47
#1 SMA wire temp, °C	255	235	220	210
#10 SMA wire temp, °C	240	242	245	260
Air inlet temp, °C	21	135	165	179
Air outlet temp, °C	60	145	170	172
Time to open clearance, s Analytical	18	17 (13)	17	16 (10)
Time to tighten clearance, s	14	16	18	24

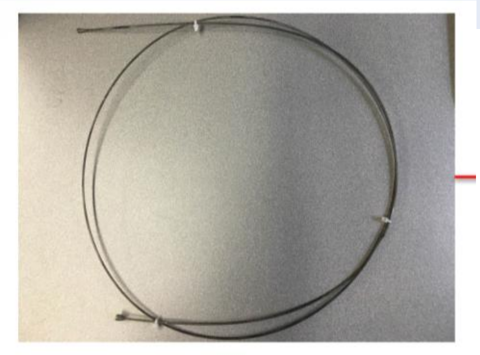
- The average response time of full deactivation (17 seconds to widen clearance to the max) for all the test conditions is 5~6 times faster than the currently prevalent active case cooling (ACC) method (60~90 seconds).
- The clearance modulation for all test conditions are within 0.021” to 0.030”. which meets the requirement of 0.020”.
- Very low power consumption (50 watts/BOAS or 1.5 kw /engine).

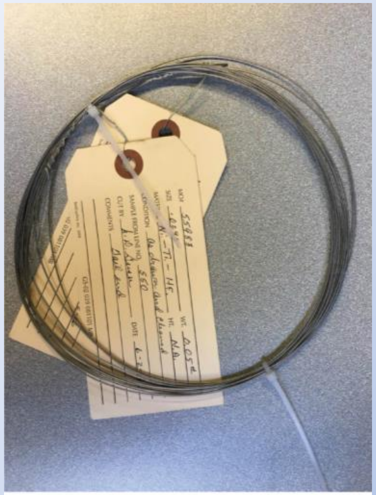
High Temperature SMA Development

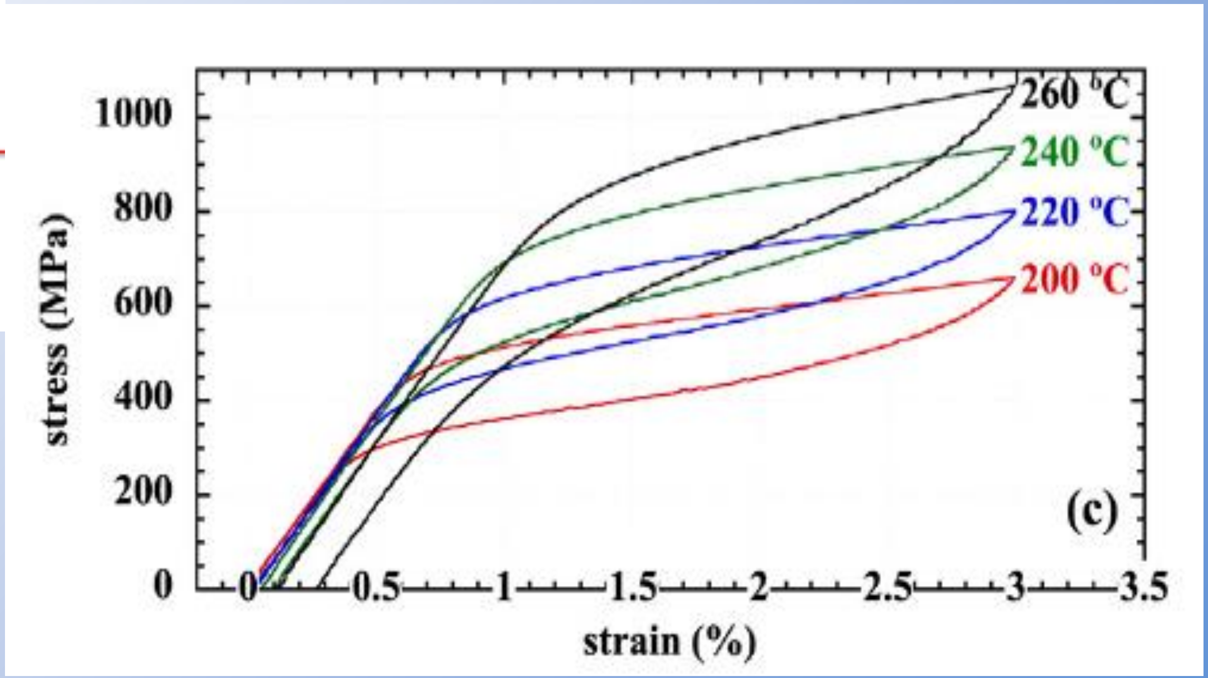
- A Variety of HTSMA materials researched.
- Two step approach adopted for near term and long term development (MTSMA and HTSMA).
- Three material composites are evaluated.
  - Ti-Ni-Pd; Ti-Ni-Hf and Ti-Ni-Pd-Hf alloys
- One material, Ti-Ni-Hf, selected, hot rolled, drawn into thin wires and used as the primary actuation muscle.
- Data show promise for phase transformation at approximately 220 °C.

Medium Temperature SMA (MTSMA)

$Ti_{50.3}$ -Ni-Hf_{20} alloy hot rolled and drawn to useful wire form 0.75 mm







Characterization at elevated temperatures

High Temperature SMA (HTSMA)

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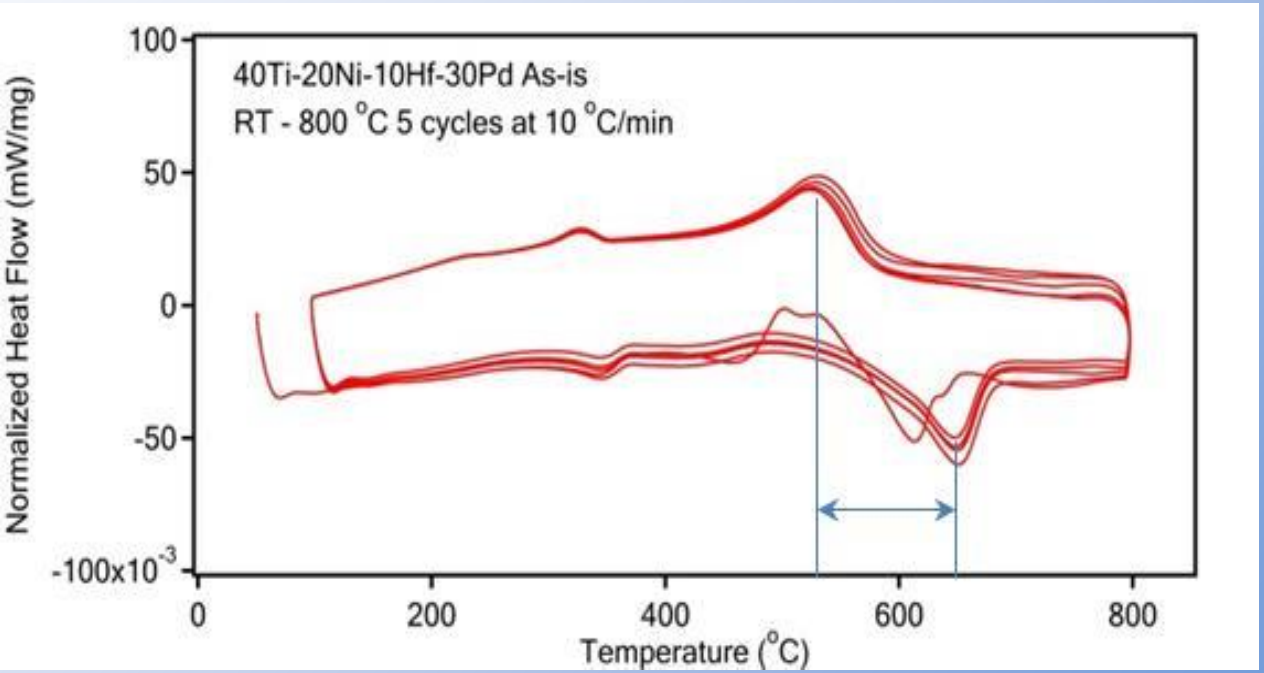
$Ni_{10}Ti_{50}Pd_{40}$ and $Ni_{35}Ti_{30}Hf_{20}Pd_{15}$



Differential Scanning calorimetry test (DSC)

Preliminary Lab test shows that material phase transformation occurs below and above 600 °C

No Technical Data subject to EAR or ITAR

Summary

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Accomplishment

- Verified engineering feasibility of low thermal mass active truss for fast response tip clearance modulation. Experimentally validated the key performance on bench test.
- Demonstrated the response 5 times faster than prevalent ACC system.
- Designed actuator that meets the key mechanical requirement (displacement, force and power) for open loop binary tip clearance modulation. Working temperature up to the limit of MTSMA (220 °C).
- Manufactured and processed Ti-Ni-Hf MTSMA into useful thin wire form.
- Developed integral thermo-fluid-mechanical tool and model for assisting design and optimization.
- Developed challenging manufacturing techniques of the actuator wire termination.

Future work

- Full characterization of promising high temperature SMA, Ti-Ni-Hf and Ti-Ni-Pd-Hf alloys (600 °C) that ultimately enable the turbine ACC and their development into useful forms for actuator.
- Investigation of actuator system reliability, durability and long term stability.
- Implementation of closed loop control with tip clearance sensor in hot airstream.

Distribution/Dissemination

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In 2015, NARI awarded ARMD LEARN Fund grants to make deliberate investments in early-stage and potentially revolutionary aviation concepts and technologies that are aligned with NASA's mission. These grants went to teams external to NASA. The objectives of this one-day seminar are to increase awareness of LEARN activities within NASA projects, to provide technical feedback to LEARN principal investigators, and educate/inform the public. This will help facilitate transfer of LEARN-developed technologies within NASA and disseminate LEARN findings to the external aeronautics community, including academia, industry, and the general public.

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