Development of High-Temperature Shape Memory Alloys for Aerospace Applications

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DRJ: 49 Machine shop (Ubienski, Panzanella, Brinkman, et al.)

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Dynalloy: Jeff Brown

Funding Sources:

RAC, UEET/IPSFT, QAT, Prop21, **IR&D**

Design of New Materials

1. **Define** – objective, goals, approach, boundaries, constraints, etc., in terms of 1-2 main properties
2. **Focus** – on the most critical properties
3. **Understand** – the controlling/fundamental mechanisms
4. **Manipulate** – composition, structure ➔ properties
5. **Test and Confirm** – determine if the material meets your requirements – ***preferably in a realistic environment***

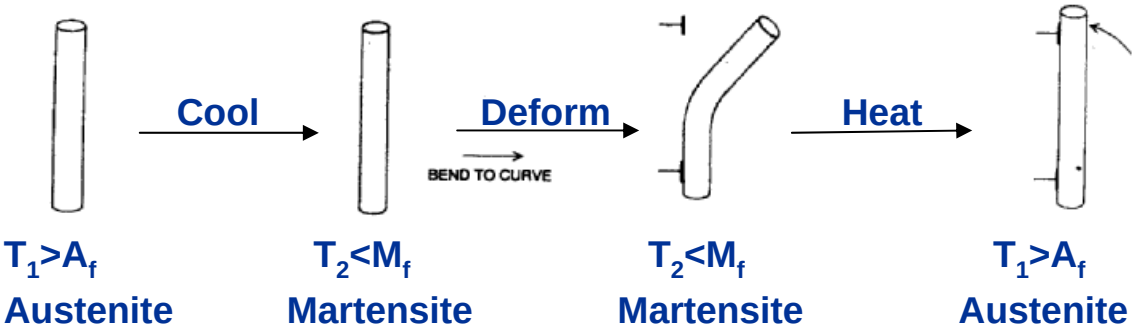
Repeat As Necessary

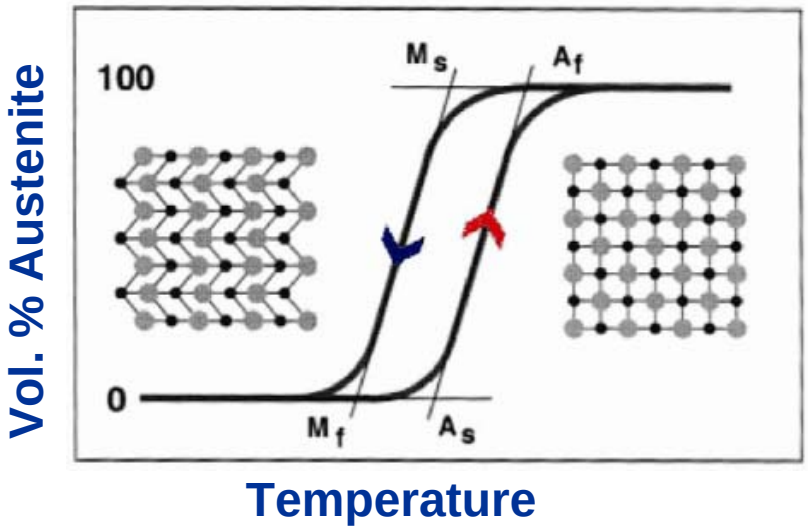
Objectives:

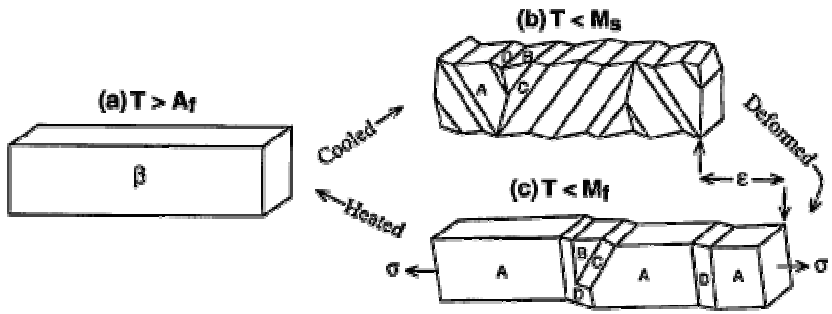
- Develop ***high-temperature*** shape memory alloys (HTSMA), with ***high-work output,*** based on derivative TiNi or TiX compositions, for ***aerospace applications***
  - Optimize and mature current 300 °C alloys (represents significant improvement compared to commercial alloys limited to ~70 °C)
  - Develop new alloys for up to 500 °C capability
- Secondary objectives
  - Develop technologies for processing SMA in product form desired for the application (e.g., rod, wire)
  - Characterize physical, mechanical, and shape memory properties sufficient for Preliminary Designs
  - Integrate these new materials into actuator design concepts and bench test designs

Shape Memory Alloys – Alloys that have a "memory."

These materials can be deformed at low temperature and recover their original shape upon heating. Shape Memory Effect



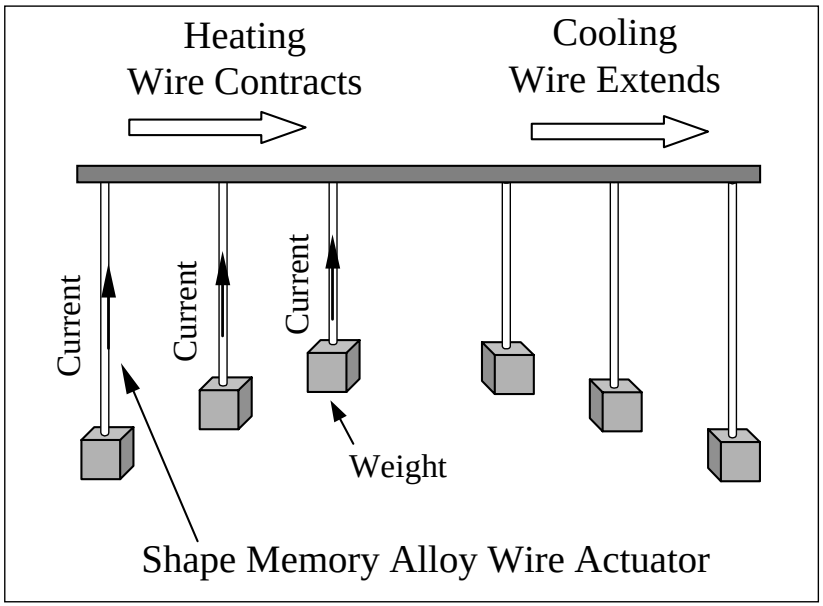


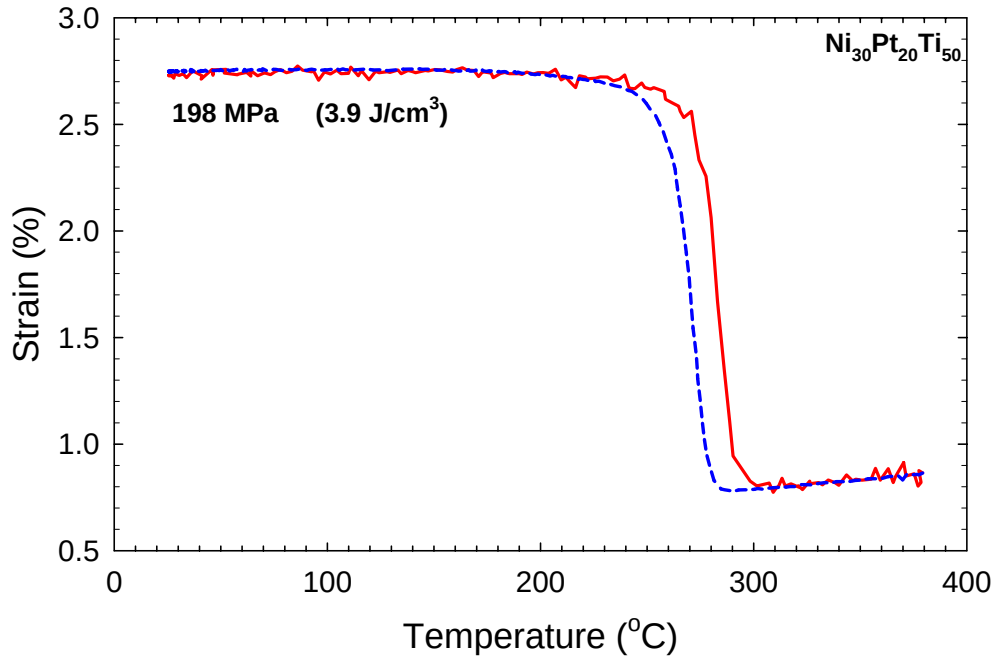


Shape memory effect is caused by a reversible change in crystal structure: the structure transforms from the high temperature Austenite to low temperature Martensite phases

Shape Memory Effect vs. Work

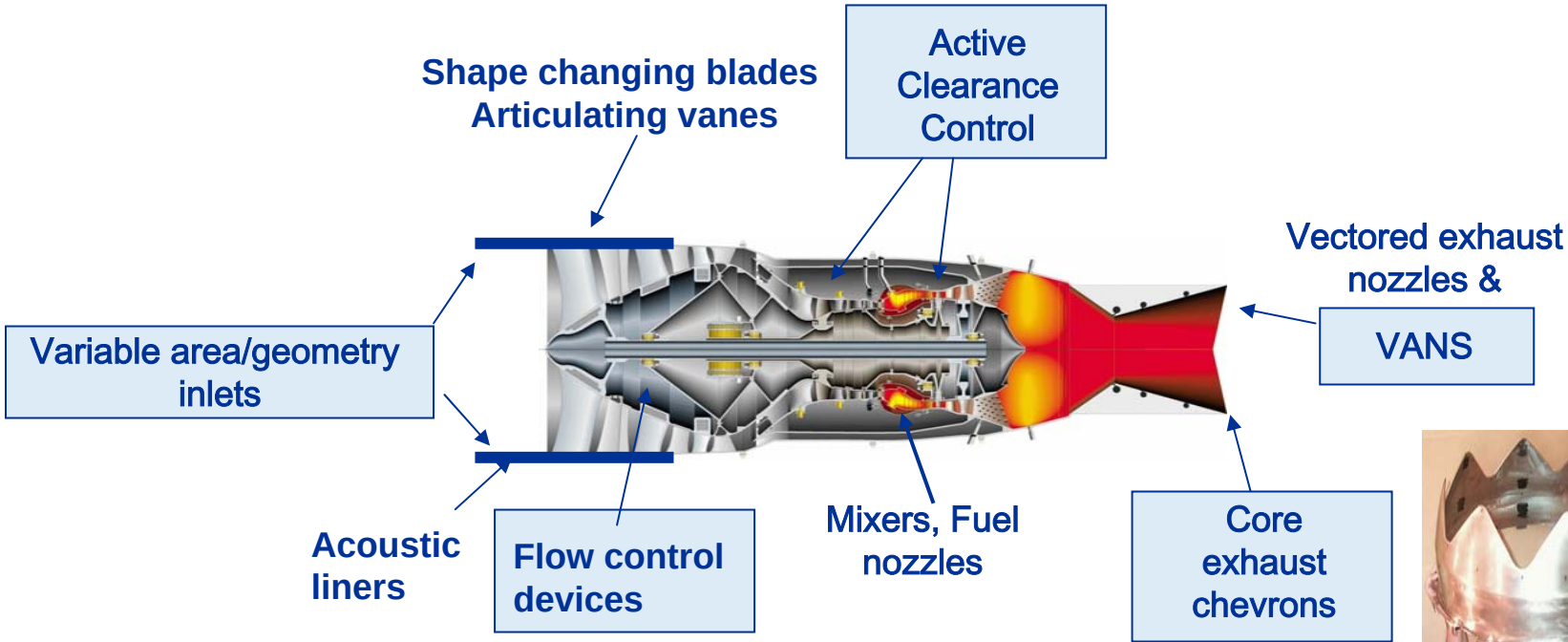
- **Shape Memory Effect** – is shape change under stress-free (no-load conditions)
- **Work** ($\int \sigma \, d\varepsilon$) – shape change against a significant bias force: e.g.,
  - The material itself acts as a compact, solid-state actuator





At 4 J/cm^3 a 44 mil wire 25" long is capable of lifting 44 lbf 0.5"

High-Temperature Shape Memory Alloys are an *enabling* technology to a host of "smart" structures in jet engines



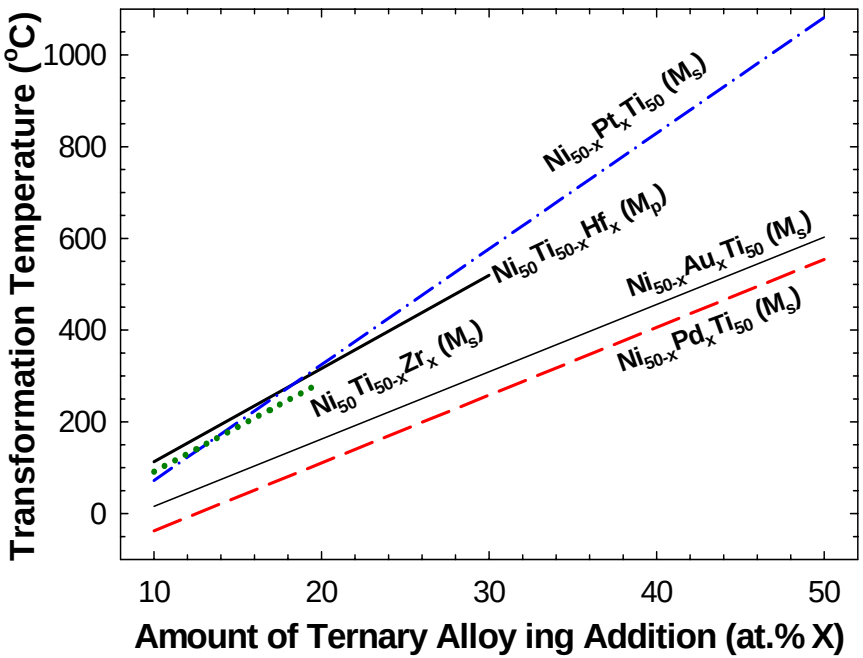
- High force per volume/weight - compact, lightweight
- Solid State - eliminates hydraulics, pneumatics, mechanical systems
  simple, frictionless, quiet, maintenance free
- Passive control - eliminates sensors, electronics
- Can be actively controlled for high-force, precision movements

Design of New Materials

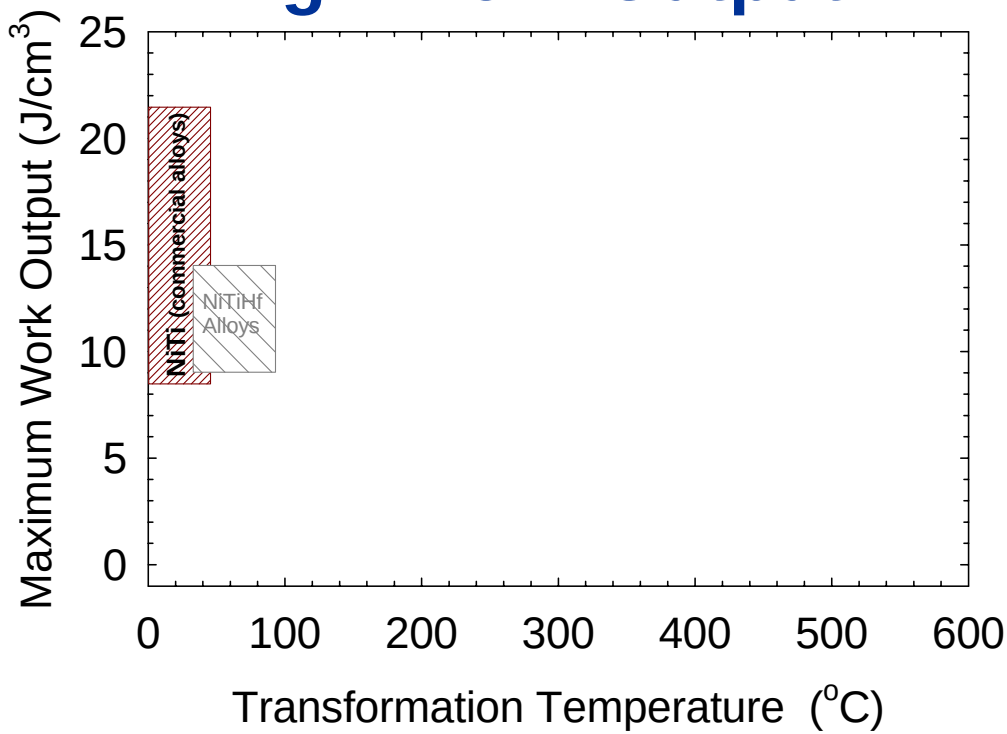
1. **Define** – objective, approach, goals, boundaries, etc.
2. **Focus** – on the most critical properties
   - High temperature capability ⇨ high trans. temp.
   - Actuator ⇨ good work output
   - Applications ⇨ correct product form (i.e., wire)
3. **Understand** – the controlling mechanisms
4. **Manipulate** – composition, structure ➔ properties
5. **Test and Confirm** – determine if the material meets your requirements – ***preferably in your application***

Prior Art -- Development of High-Temperature Shape Memory Alloys

- **High Temperature**

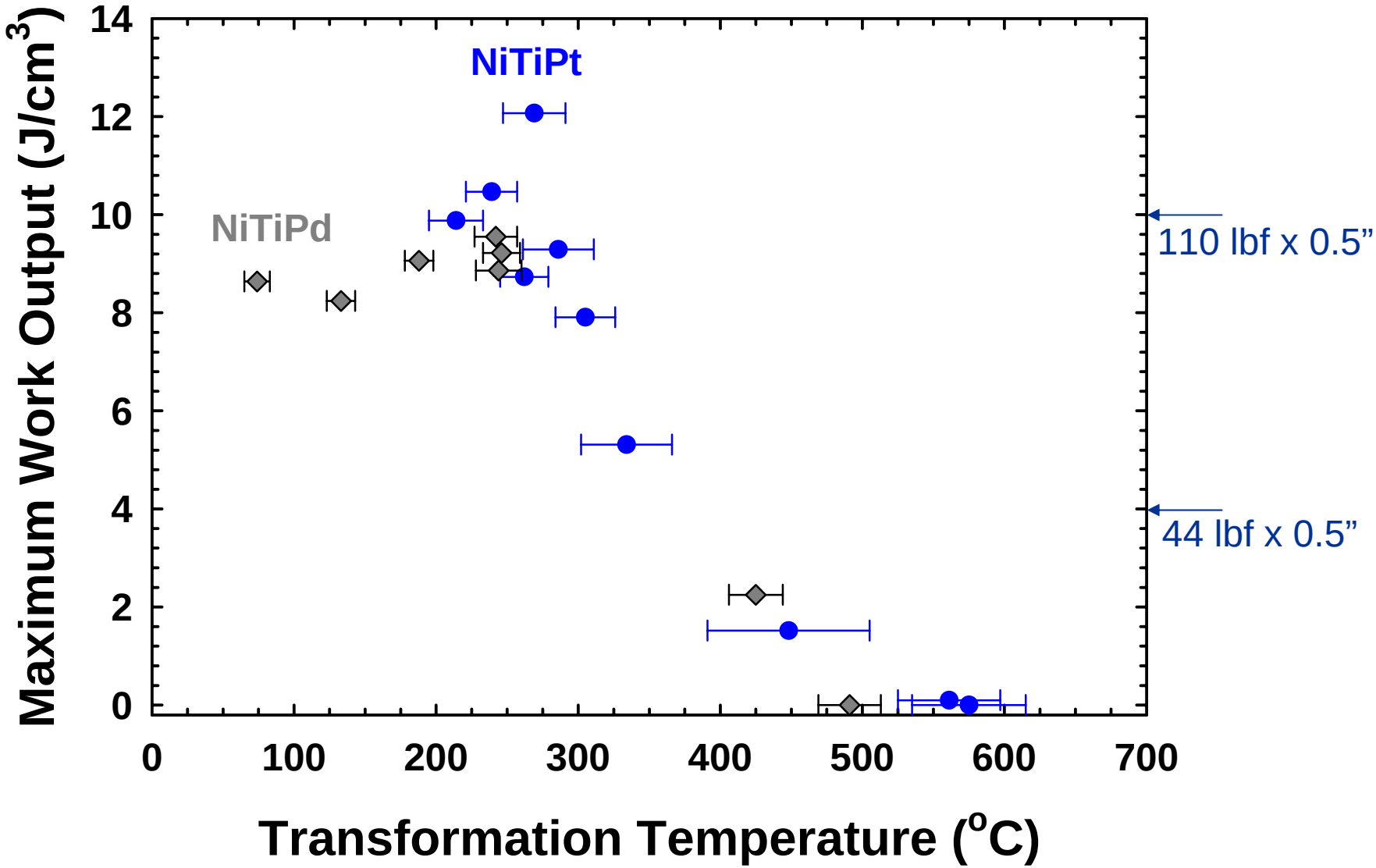


- **High Work Output**

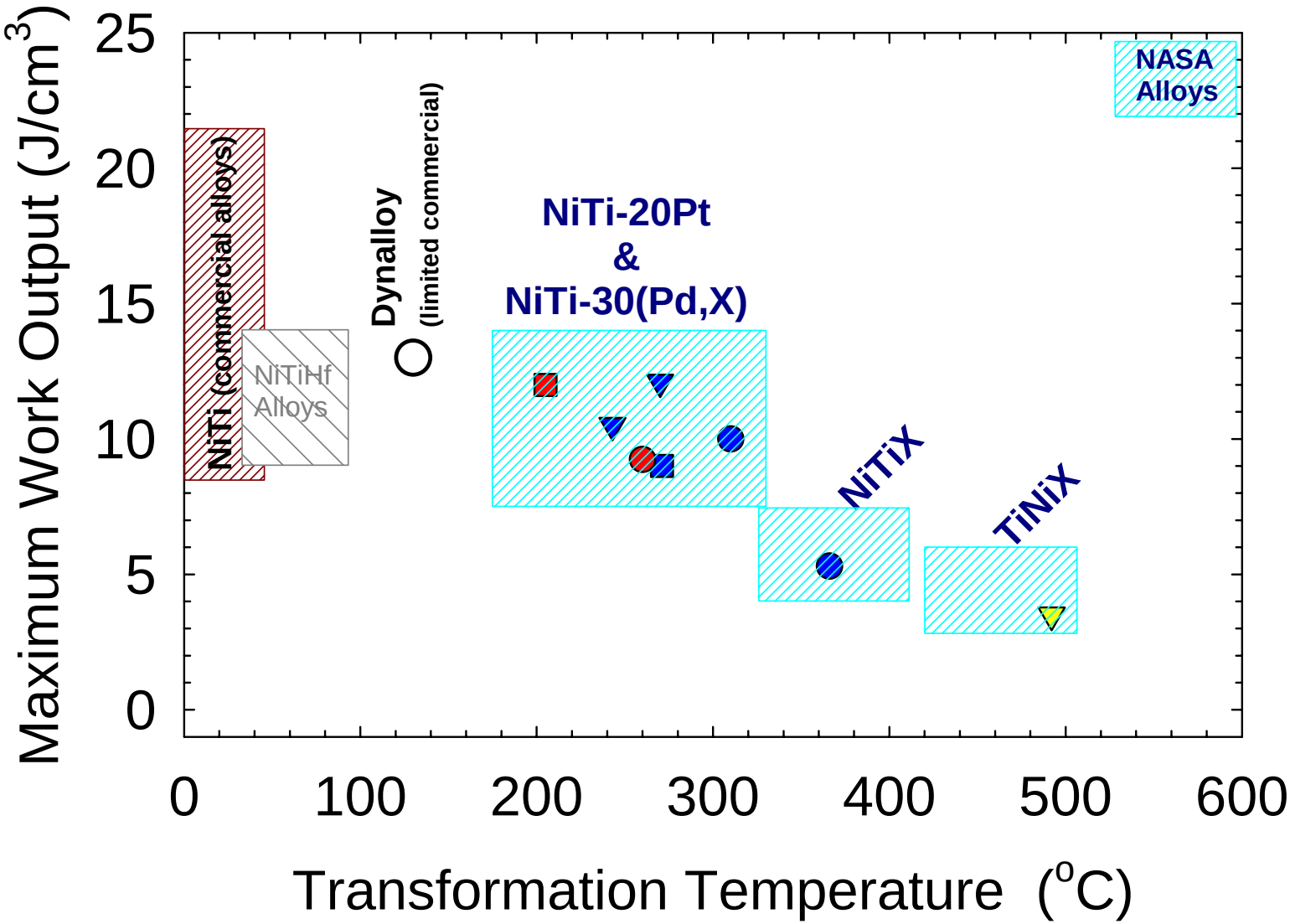


- High transformation temperature known for almost 30 years
- Prior focus on transformation temperatures and at best SME

Work Behavior of HTSMA



Viable Alloys Based on Work Behavior Identified By NASA



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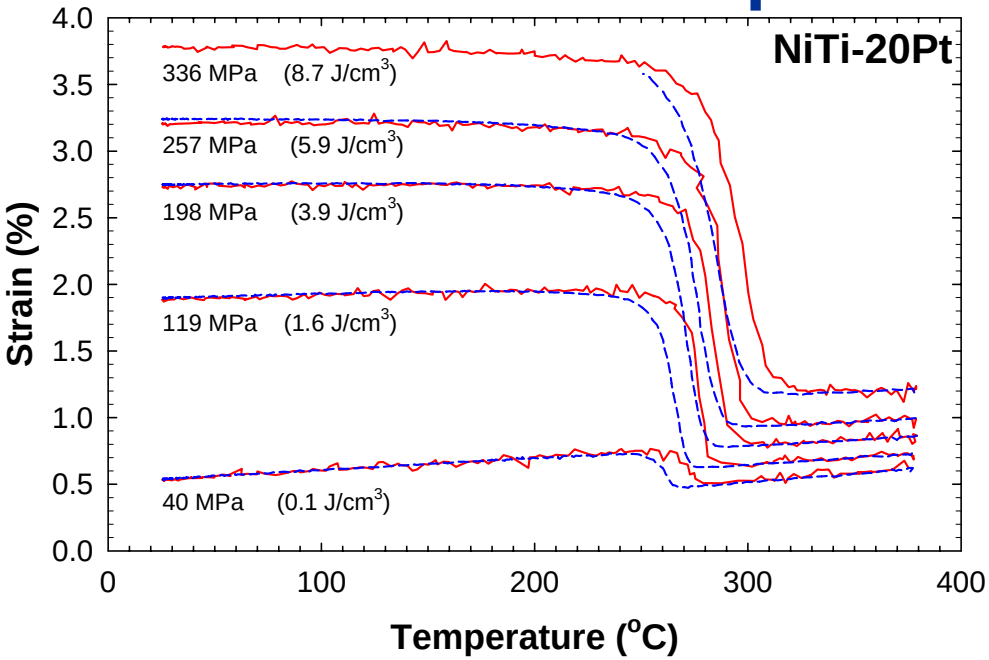
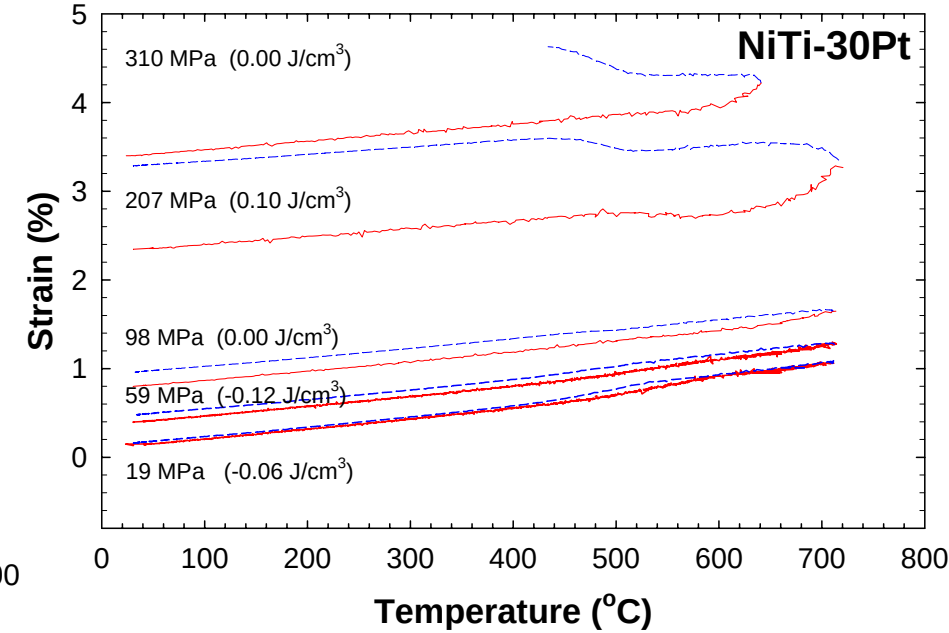
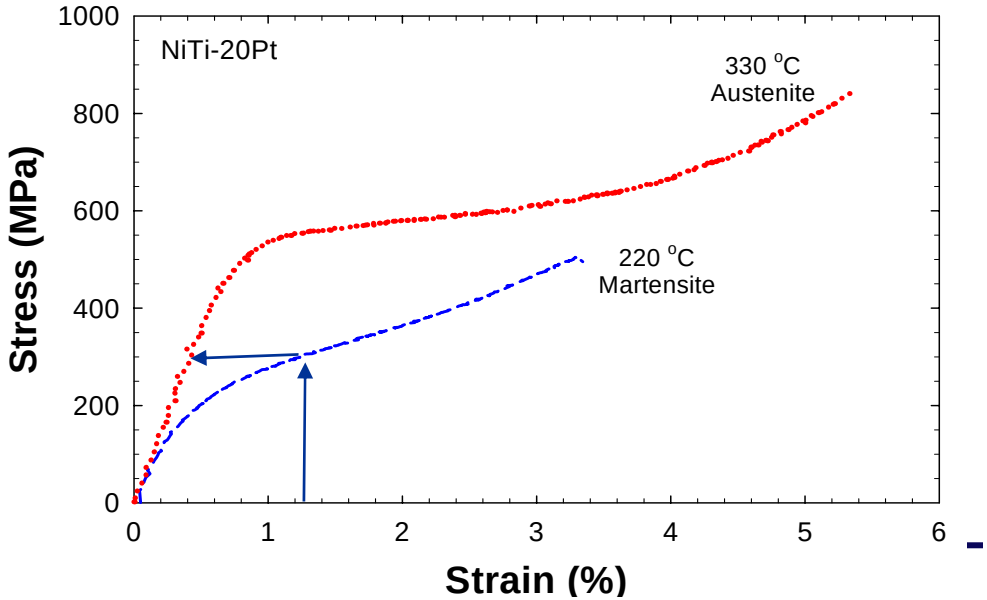
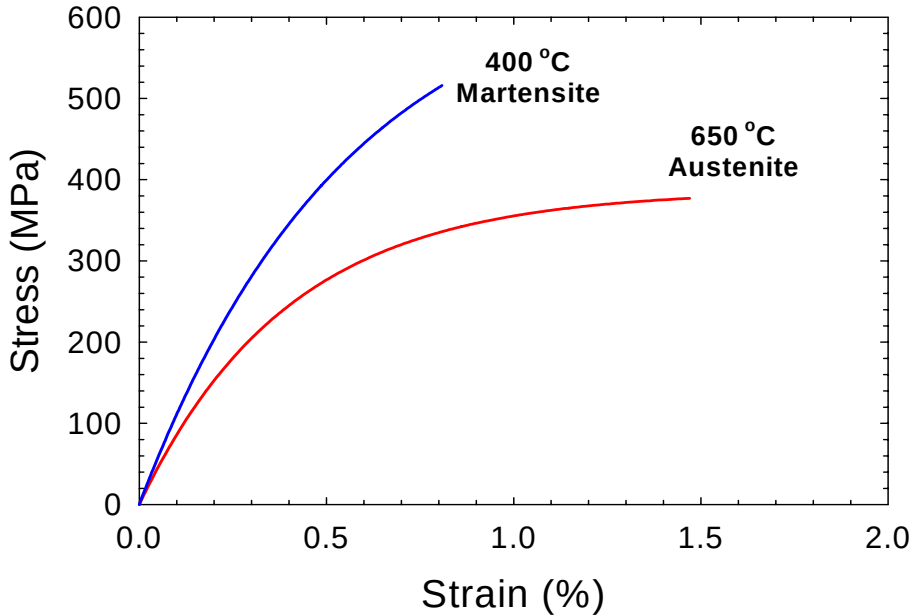
Repeat As Necessary

Understanding the Factors Controlling Work Output in HTSMA

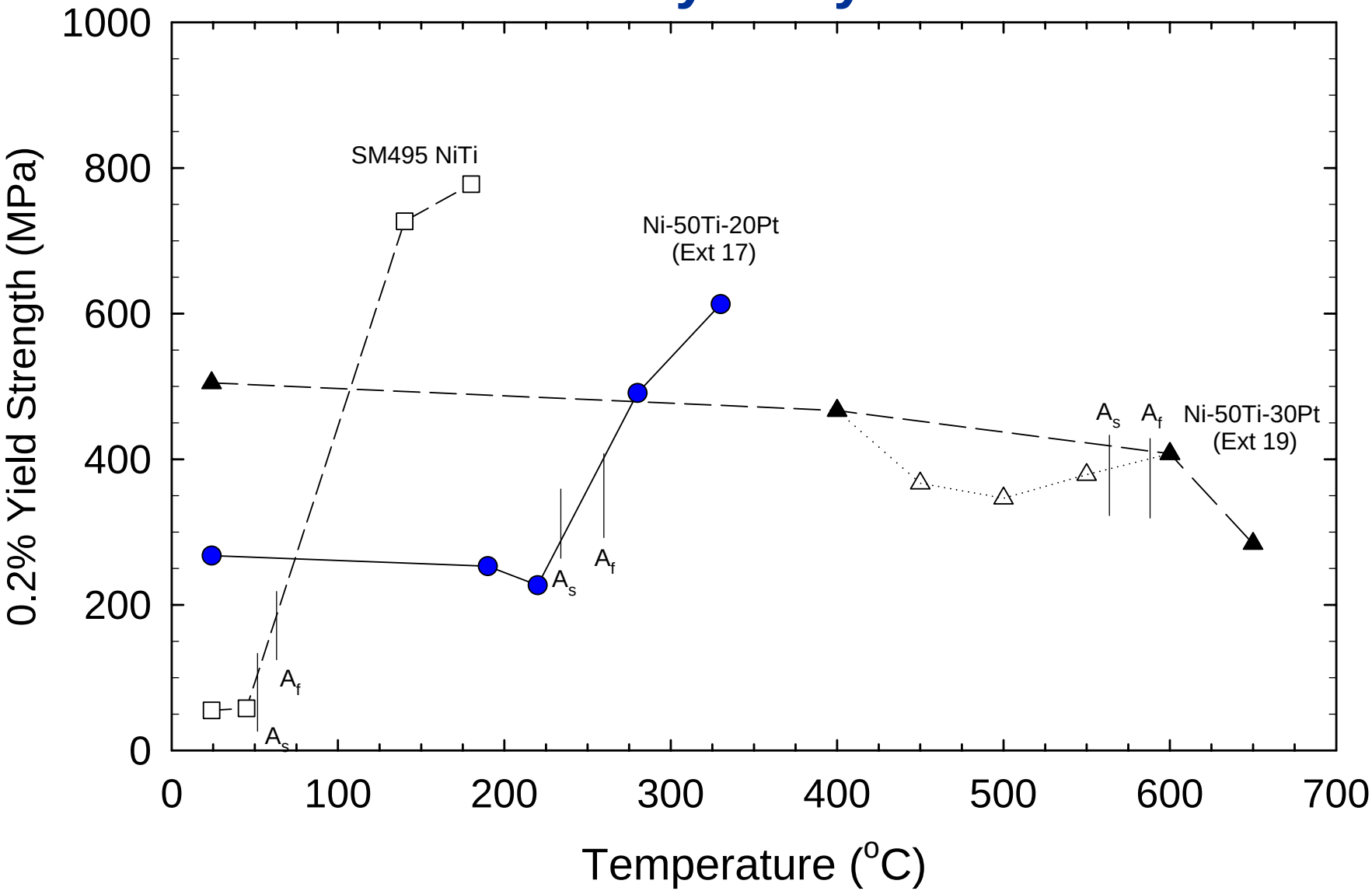




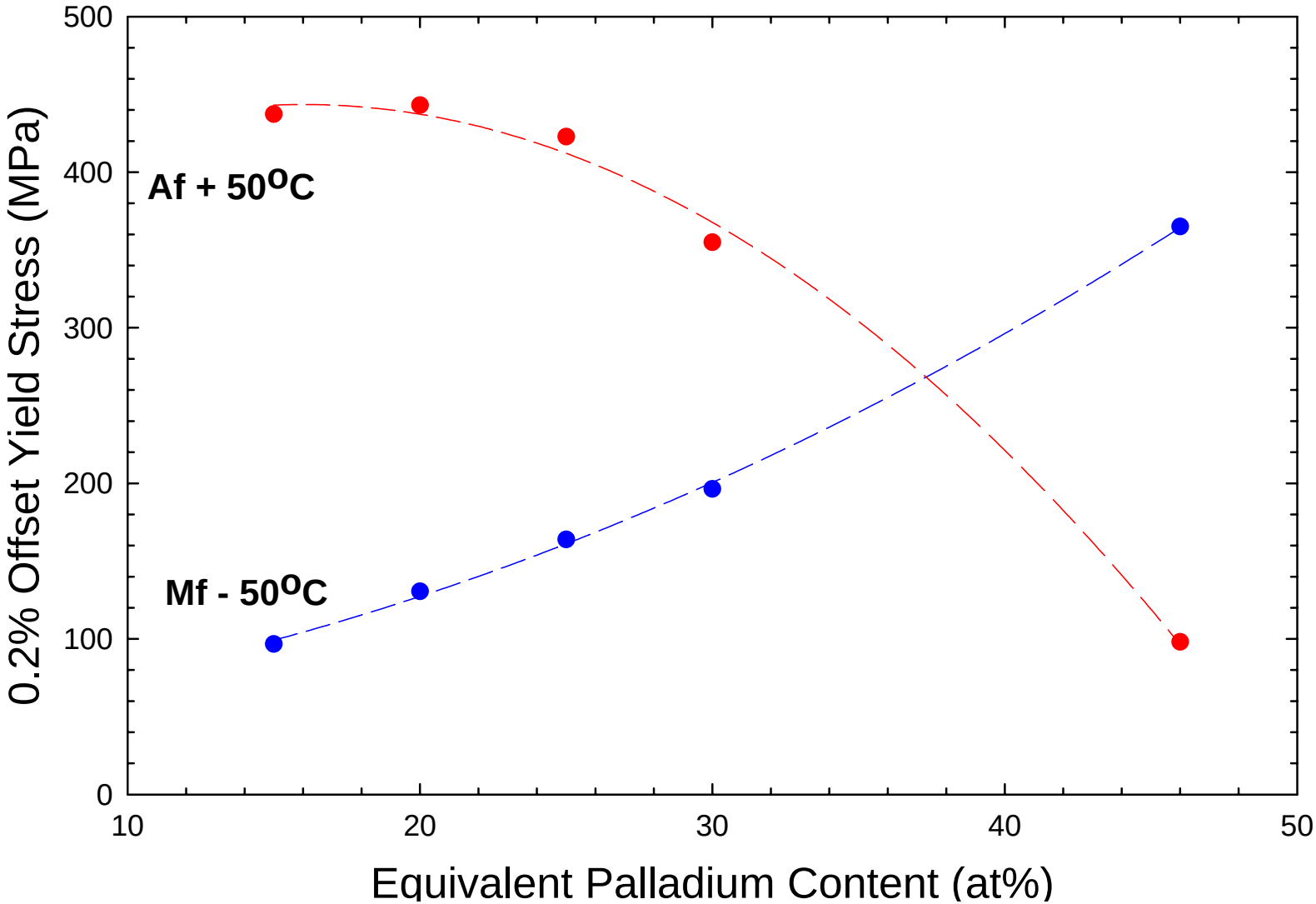




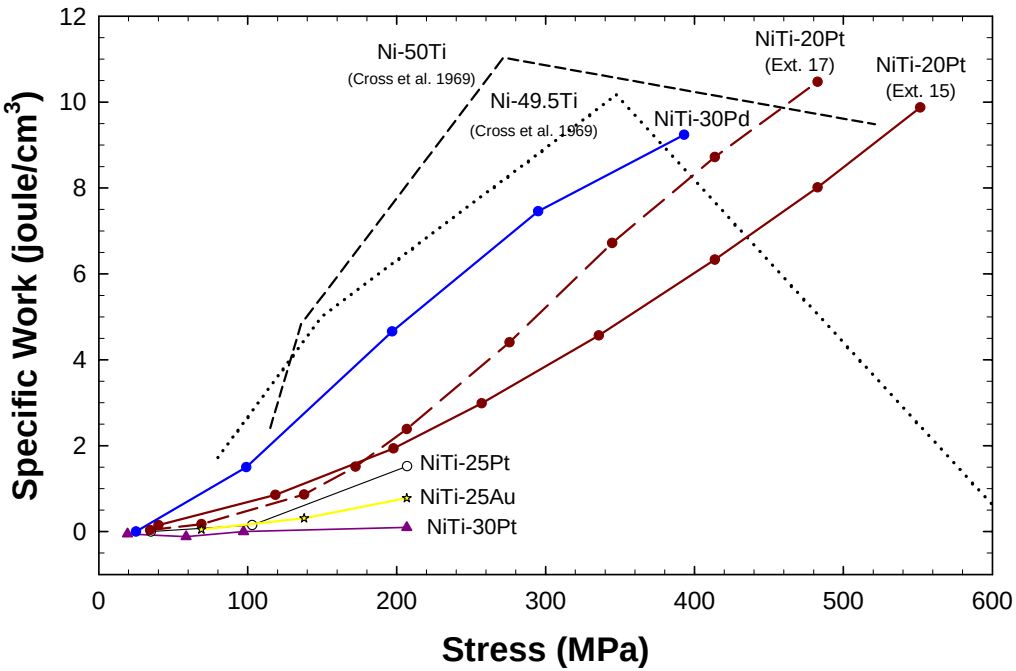
Yield Strength Comparison of Shape Memory Alloys



Yield Strength Behavior of NiTiPd Alloys

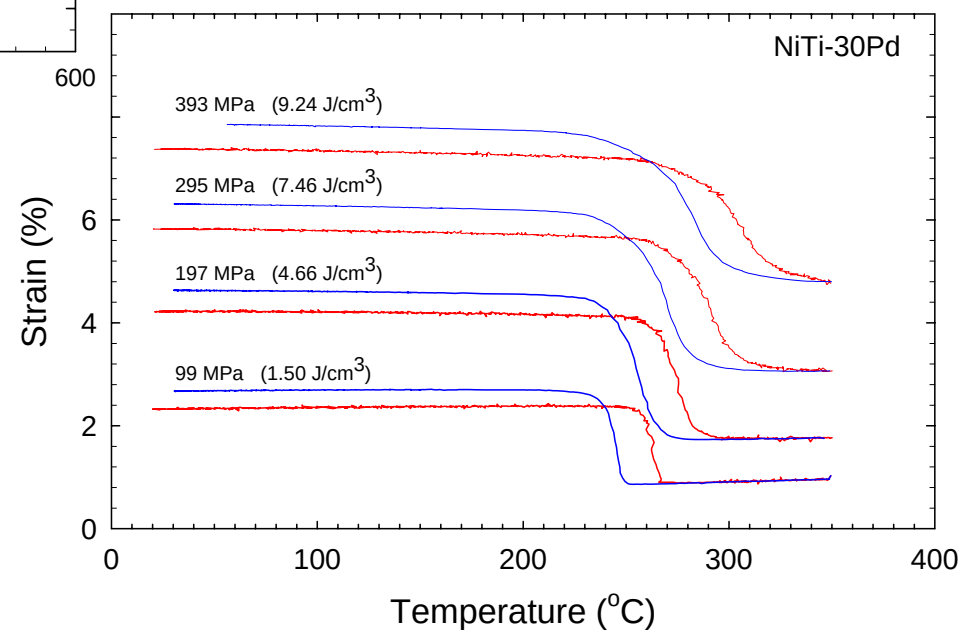


Even Good Work Capability is Not Sufficient



⇦ NiTi-30Pd alloys have transformation temperatures and single cycle work output comparable to that of NiTi-20Pt alloys

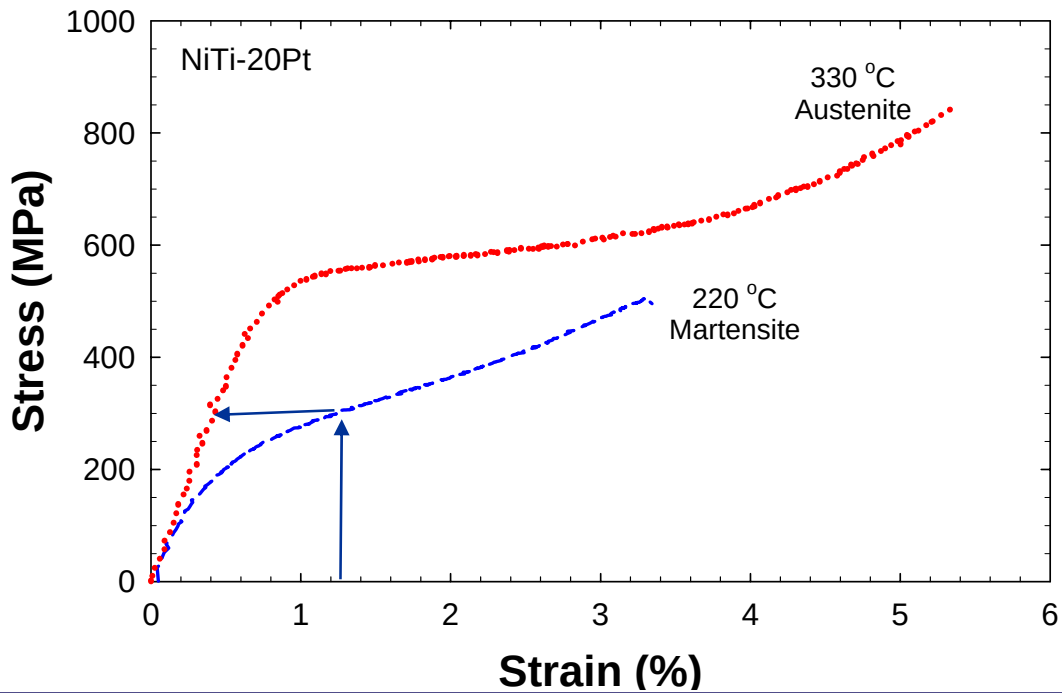
⇩ The strain-temperature loops do not close at any stress level resulting in permanent (plastic) deformation with each cycle



✖ This is a phenomenon known as "walking" and effects the dimensional stability of the material during use. It is critical to avoid walking in applications requiring repeated cycling, in order to maximize fatigue life and minimize drifting of the zero point in SMA actuators

SMA Design for Optimum Work Output and Dimensional Stability during Cycling

1. Low stress for deformation by detwinning of the martensite phase
2. Maximize the resistance of the martensite phase to slip
3. Maximize the yield strength of the austenite phase



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SMA Design for Optimum Work Output and Dimensional Stability during Cycling

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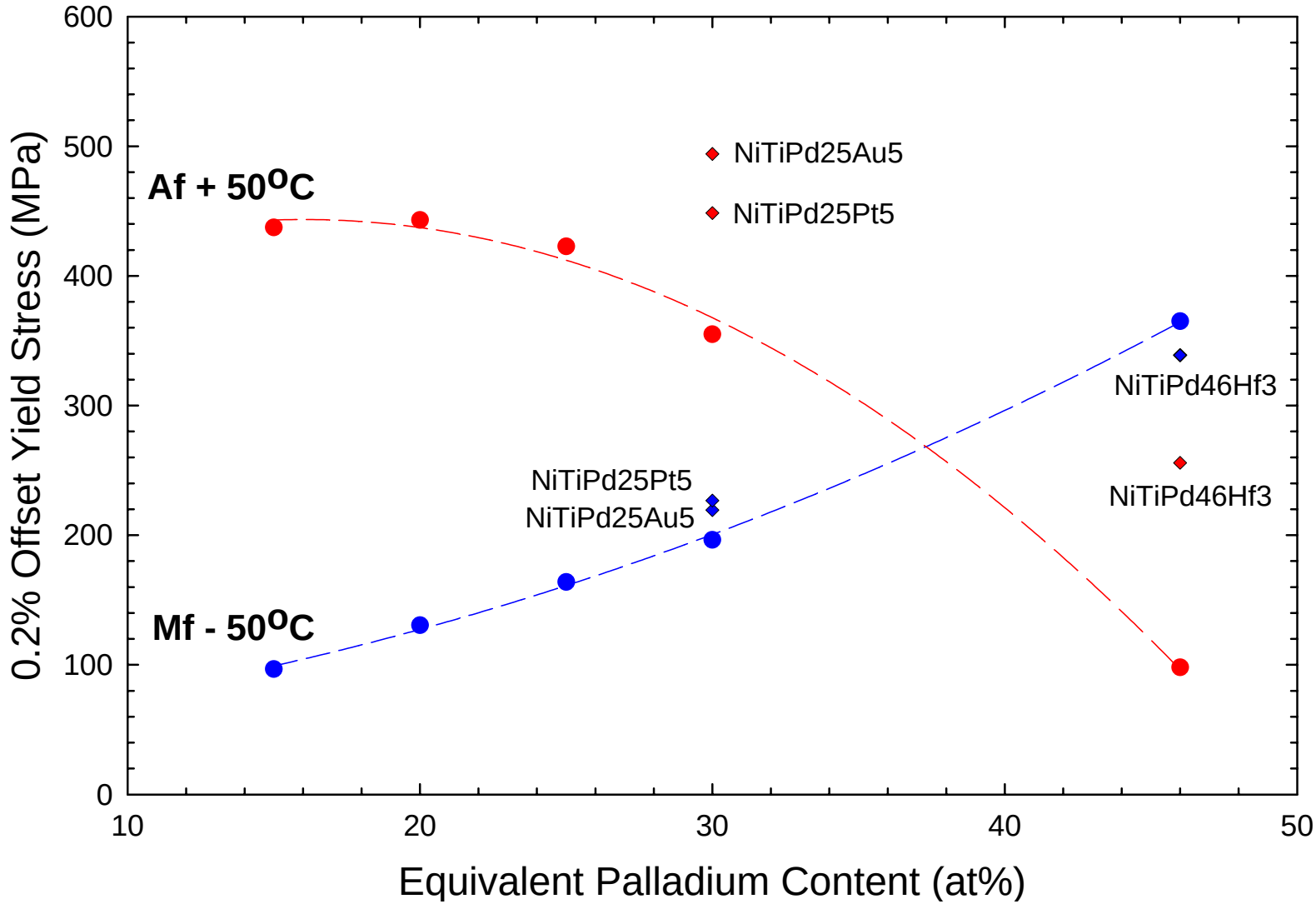
2. Maximize the resistance of the martensite phase to slip
3. Maximize the yield strength of the austenite phase

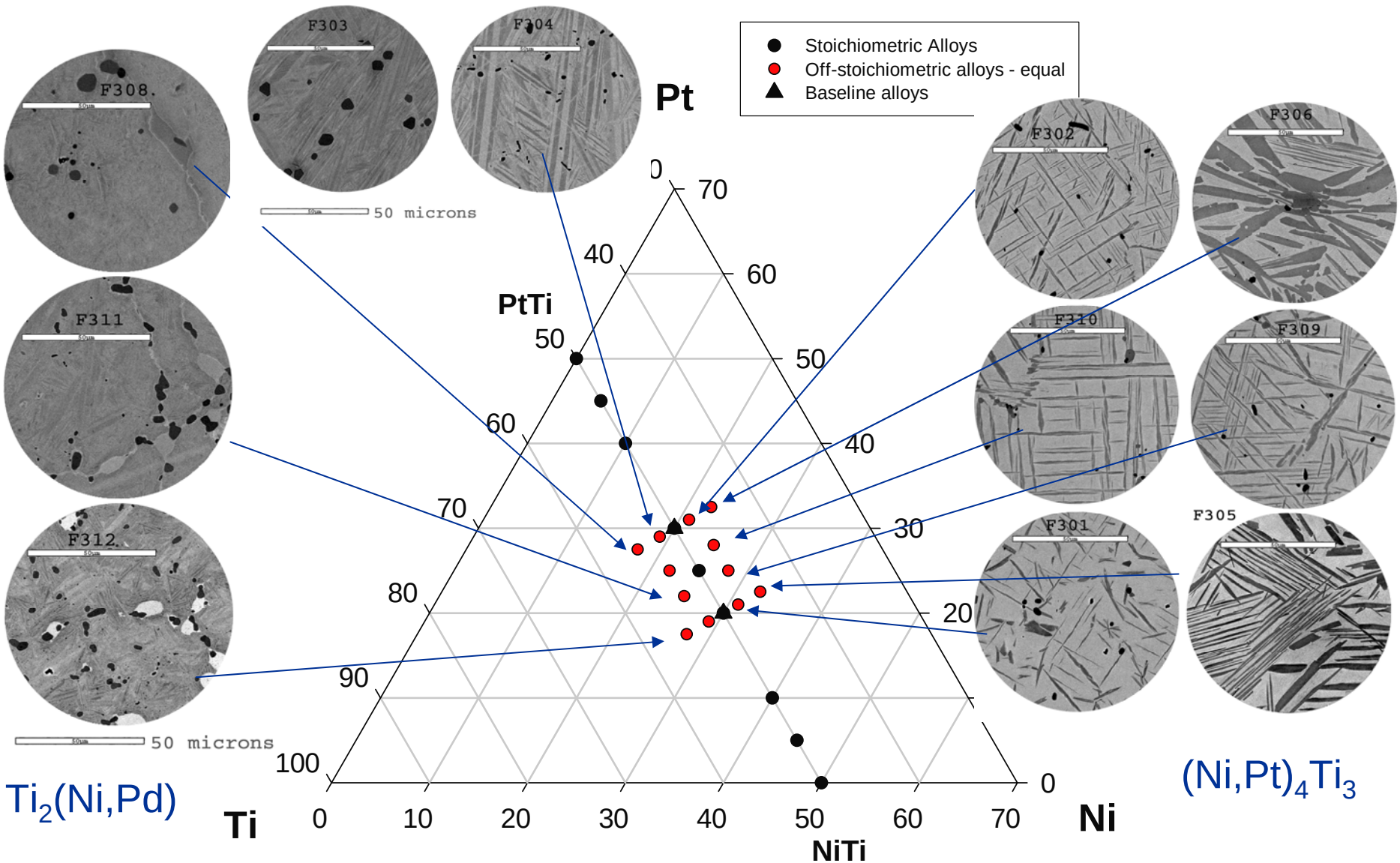
This can be accomplished by typical metallurgical processes such as:

- **solid solution alloying**
- **precipitate strengthening**
- **thermomechanical processing**

Solid Solution Strengthening: NiTiPdX Alloys



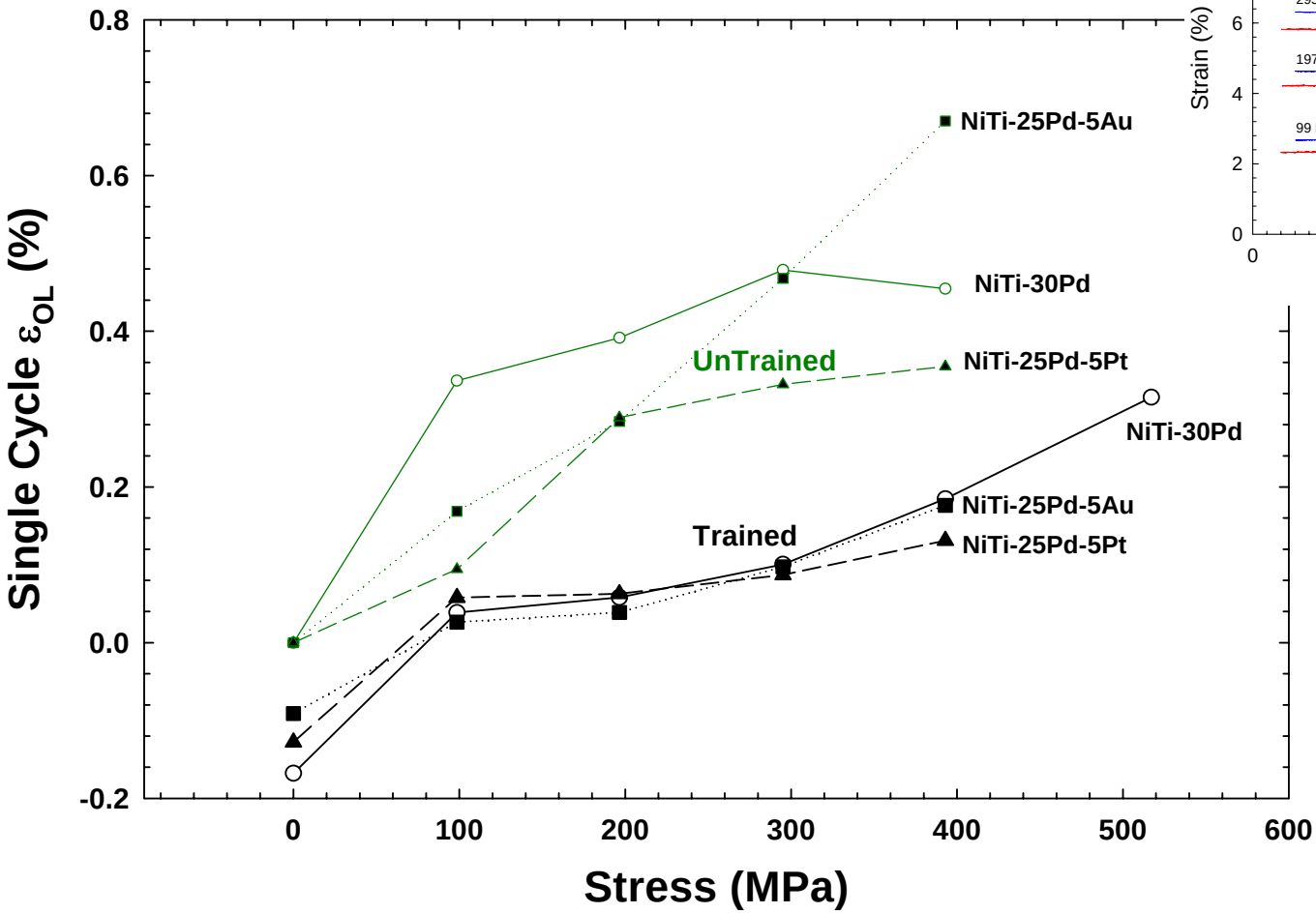
Microstructural Control of NiTiPt Alloys

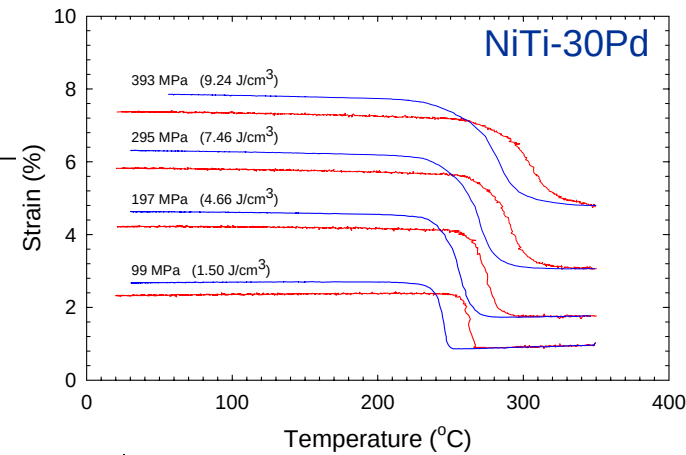


$Ti_2(Ni,Pd)$

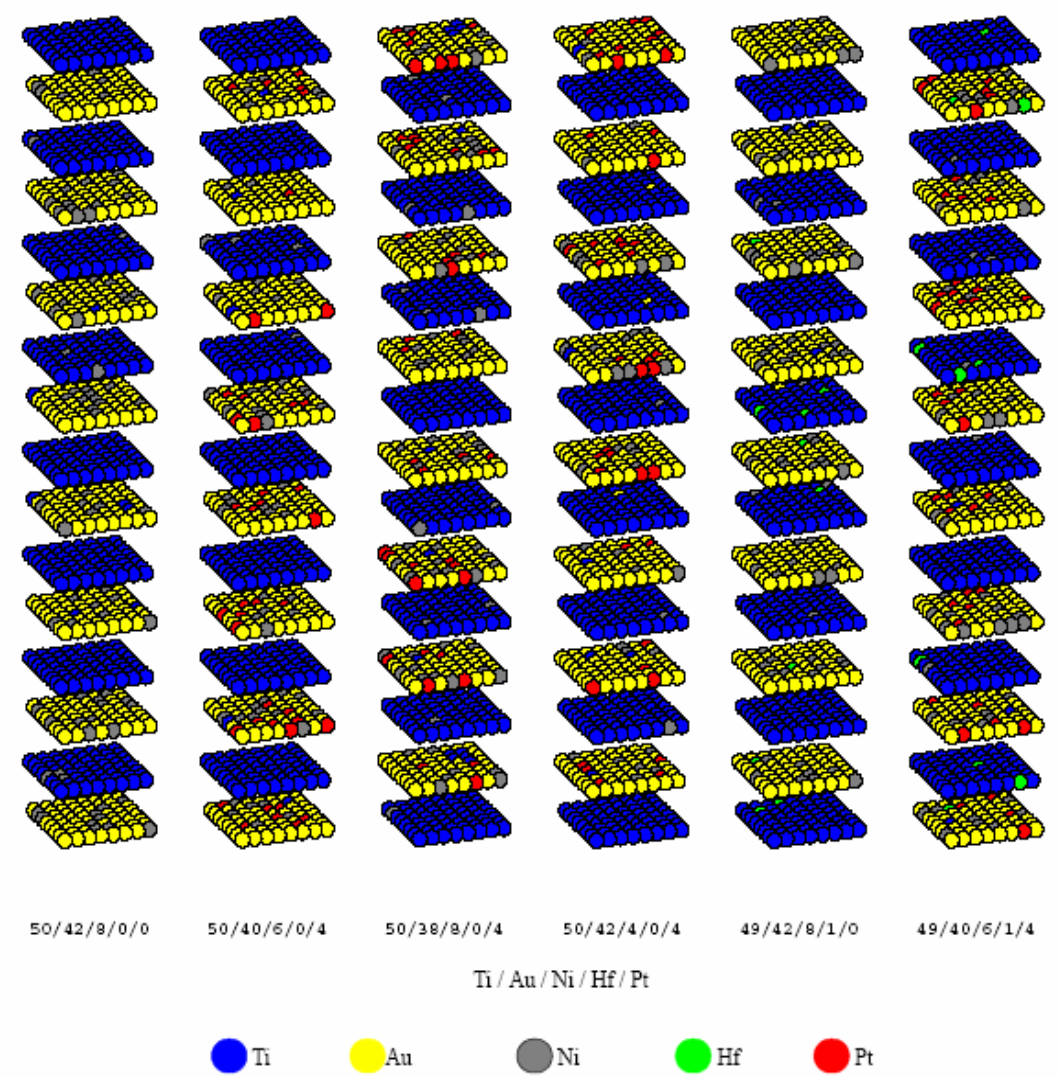
$(Ni,Pt)_4Ti_3$

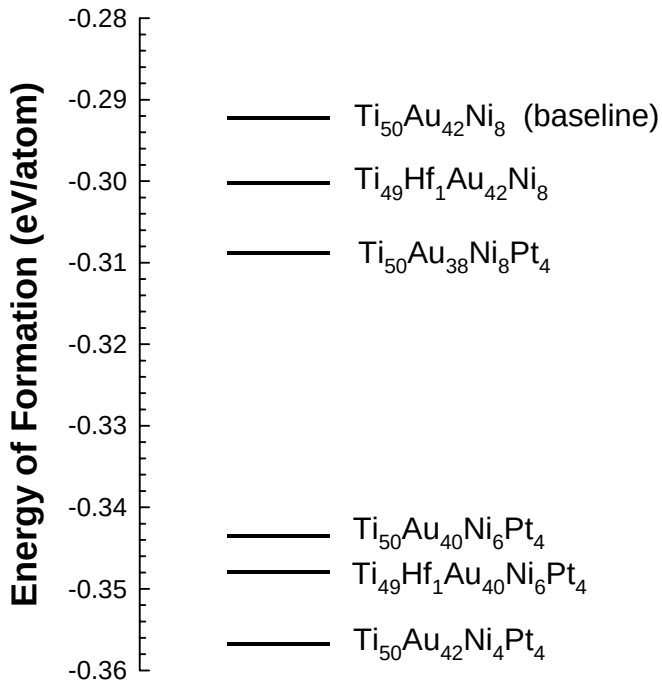
Thermomechanical Processing (Training) and Alloying Can Increase the Dimensional Stability of $Ni_{20}Pd_{30}Ti_{50}$ Alloys



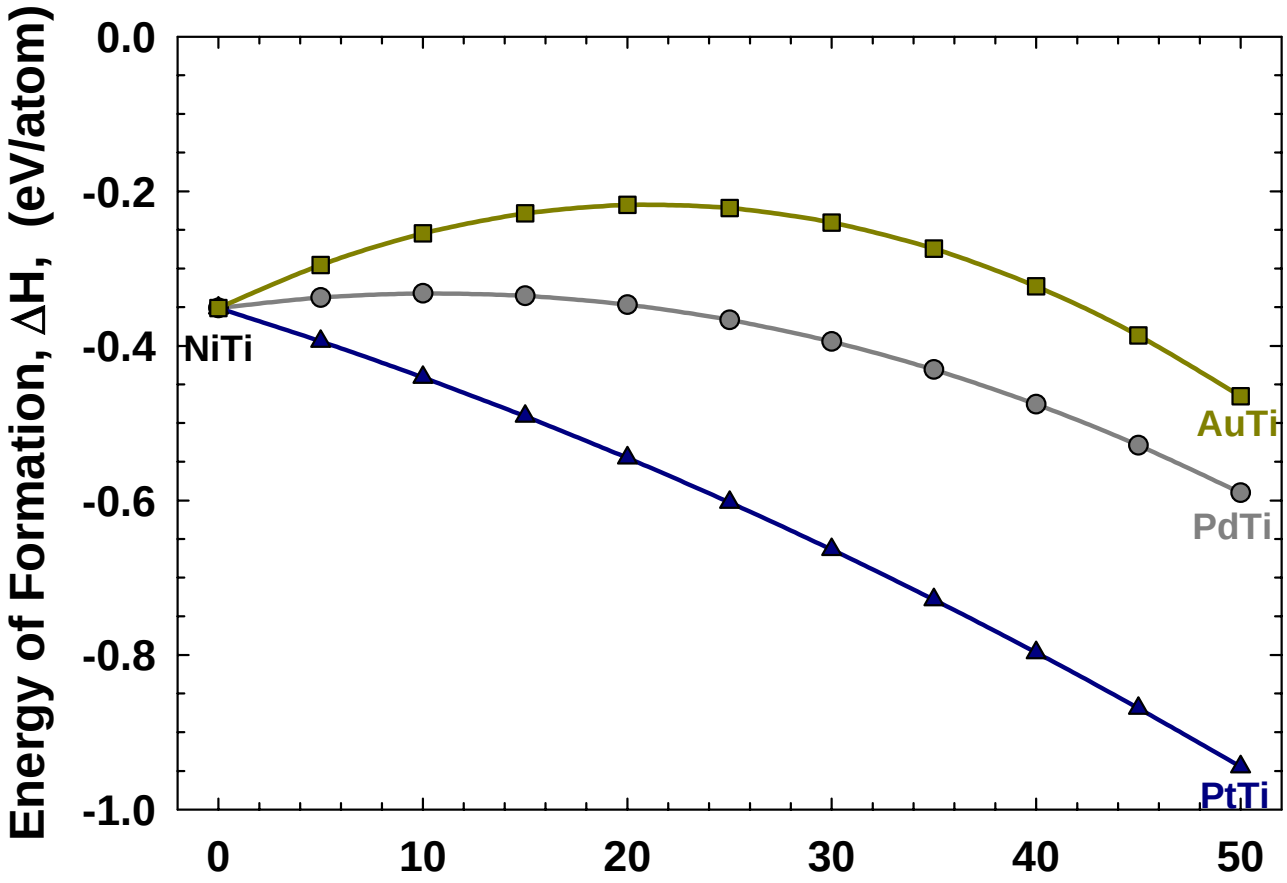


Computational Modeling as a Guide to Alloy Design





Energy of Formation for (Ni,Pt)-Ti, (Ni,Pd)-Ti and (Ni,Au)-Ti alloys in the B2-austenite Phase Calculated Using the BFS Method for Alloys



Percent Alloying Addition, X, (Pd, Pt, Au) for $Ni_{50-x}Pd_xTi_{50}$, $Ni_{50-x}Pt_xTi_{50}$, $Ni_{50-x}Au_xTi_{50}$

Design of New Materials

1. **Define** – as much as possible up front: objective, approach, goals, boundaries, etc.
2. **Focus** – on the most critical properties
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Repeat As Necessary

HTSMA Wire & Rod Production

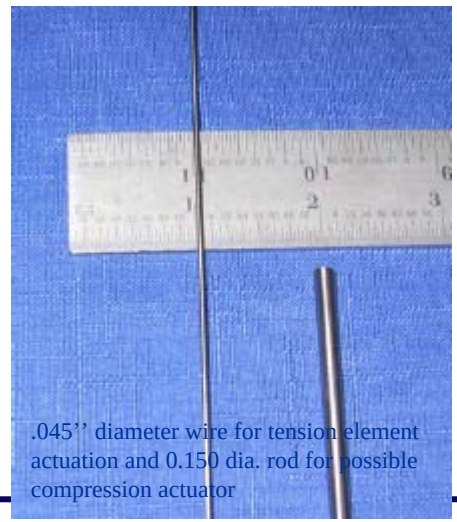
Multiple Extrusion for Rod Production

- Multiple extrusion (currently performed at Anomet, Inc.) followed by centerless grinding is a viable commercial process for the fabrication of bulk quantities of NiTiPt rod and coarse wire
  - down to 0.045” diameter
- This material has been chosen for incorporation into demonstration projects by Continuum Dynamics under two separate Phase II SBIRs
  - high speed inlet (SSBJ)
  - core exhaust chevron

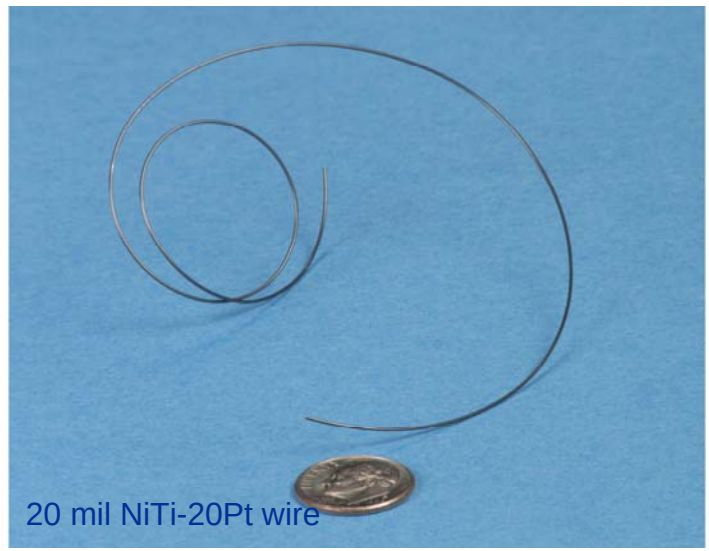
Drawing Can be Used to Produce Fine Diameter NiTiPt Wire

- Using extruded precursor rod, Dynalloy, Inc. has developed a processing schedule for cold drawing NiTiPt/Pd rod into fine wire
  - diameters less than 0.005” are possible
- Fatigue testing of 20 mil wire is currently underway at GRC

120 ft. of 60 mil NiTi-20Pt rod

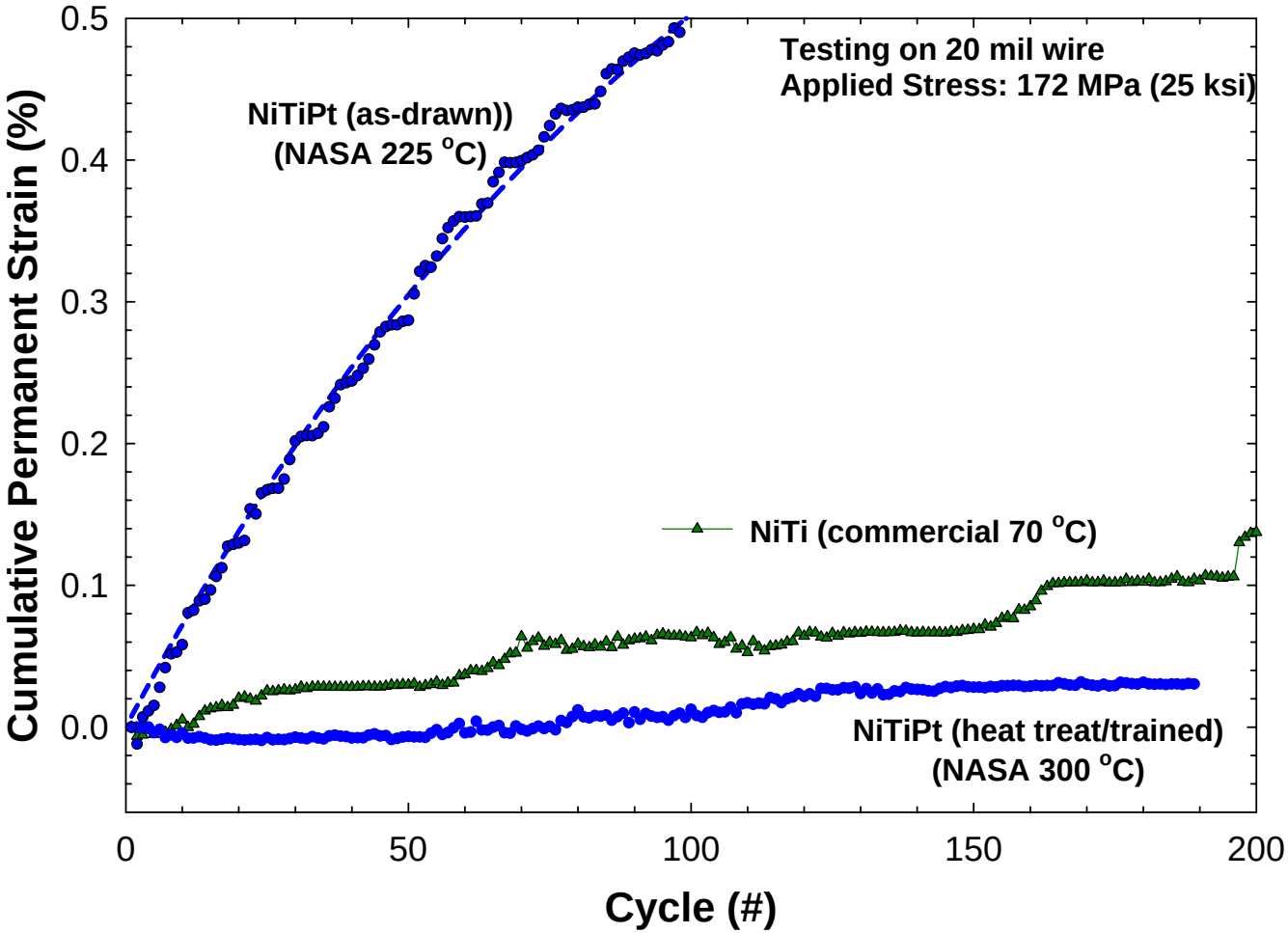


.045’’ diameter wire for tension element actuation and 0.150 dia. rod for possible compression actuator



20 mil NiTi-20Pt wire

NiTiPt Wire & Rod Post-Processing Development



- **Even though the NiTi-20Pt wire can be used to much higher operating temperatures, it is dimensionally more stable than the best commercial alloys**

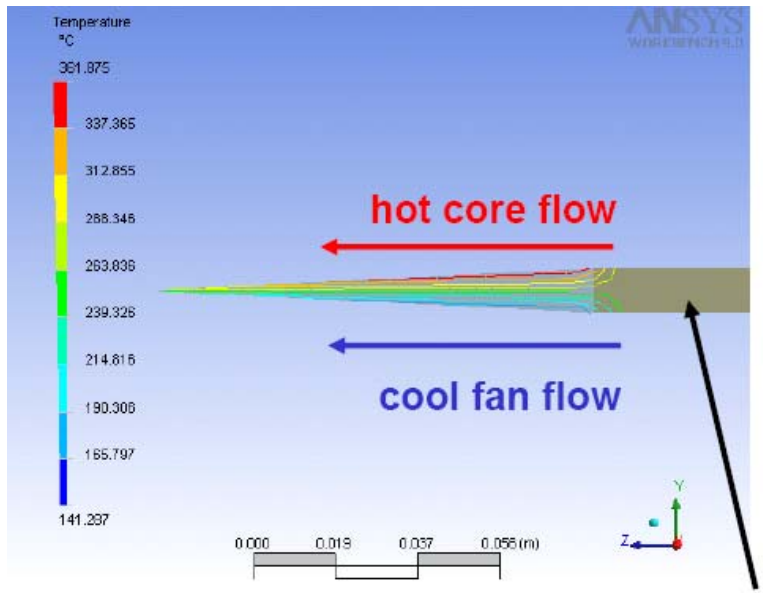
Application of HTSMA

- Processing of HTSMA in appropriate form, (e.g. wire), enables the accelerated maturation of these materials by rapid insertion into component demonstrations

- SMA's can be used in either active or passive designs.
  - Passive: The material heats up during normal engine operation and actuates automatically
  - Active: The material is used below it's transformation temperature and supplemental heat (eg., electrical resistance heating) is used to actuate "on demand."

Adaptive Chevrons For Core Exhaust Applications (QAT, Prop21)

- Need chevrons in the exhaust flow during take-off to reduce noise, and remove them during cruise to maximize fuel efficiency
- Adaptive fan chevrons developed by Boeing / NASA LaRC



- Fan exhaust gas temperature is approximately 80 ^{o}C
- Core exhaust gas temperature is approximately 650 ^{o}C

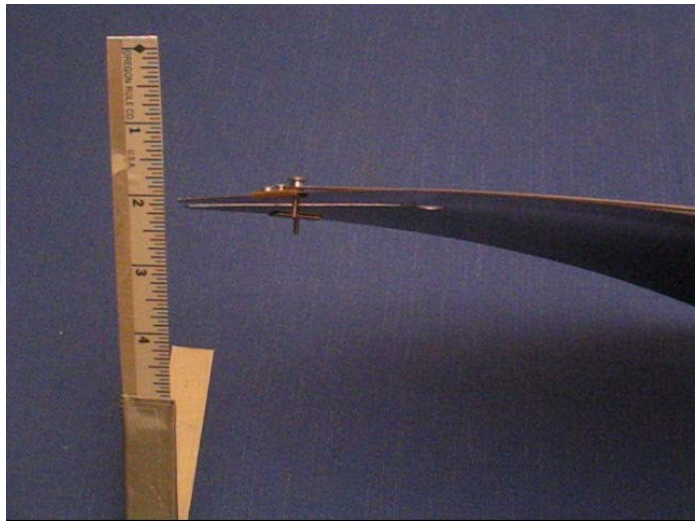
internal conduction TBD

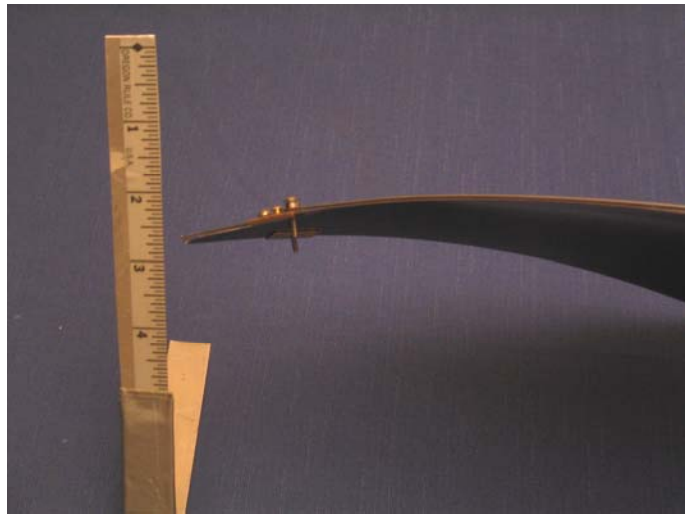
Chevron Bench Test With NiTiPt

Continuum Dynamics, Inc.

0.025” Spring Steel Chevron (8% of full scale stiffness) Actuated via NiTiPt Wire
(single strand of 45 mil dia. NiTi-20Pt Wire)

Neutral Position





Full Deflection (0.75” at tip)

- NiTiPt (high-force, high-temperature) SMA wire developed by NASA GRC used in conjunction with CDI “cut chevron design” as proof of concept for a viable core exhaust chevron
- Advantages:
  - ⇨ Concept scalable to flight hardware
  - ⇨ Design is more than 5 times more efficient than typical approach (full scale chevron could be actuated by single braid of 4-5 wires)
  - ⇨ Reproducible movement of the chevron (purely elastic); built in stop
  - ⇨ HSTMA actuator wire is not exposed to direct exhaust stream

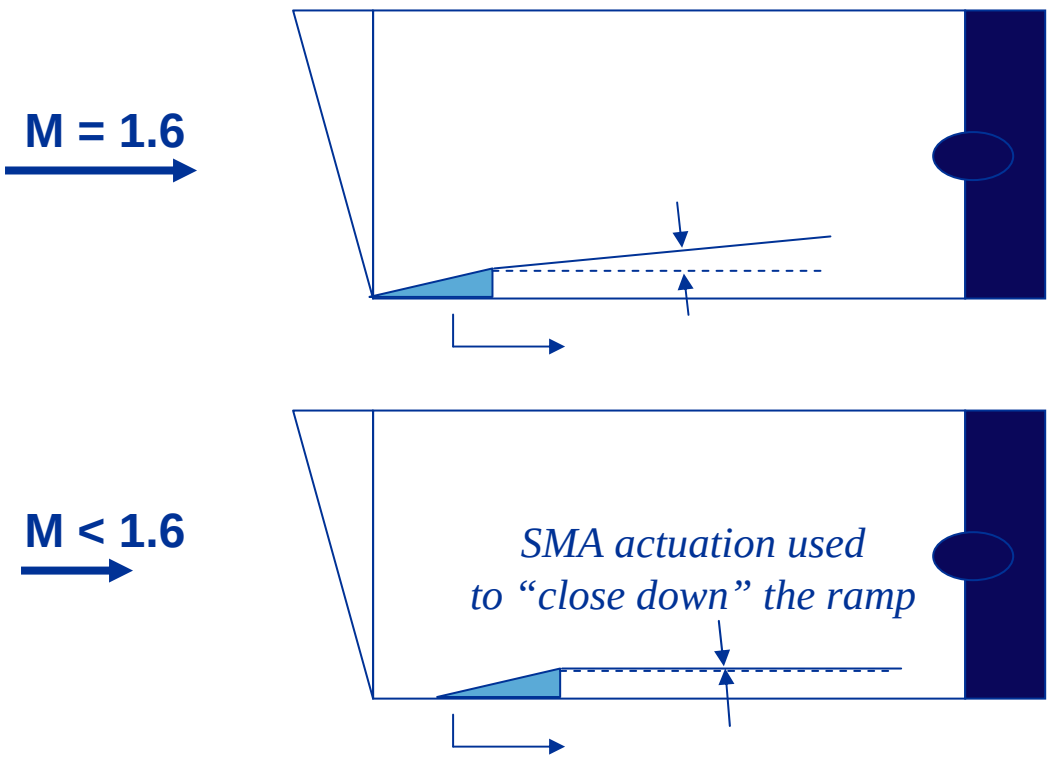
2D Inlet to be Developed by *Continuum Dynamics* to *Raytheon* Specifications Using *NASA* NiTiPt Wire

Supersonic Wind Tunnel Test Scheduled for late Summer

Raytheon seeks lightweight technology for SSBJ to adjust:

a) angle of secondary compression ramp

b) position of overall two-ramp structure for off-design flow states



Active Clearance Control Concept Can Compensate For Blade Tip Seal Wear

(With J. Decastro, K. Melcher, B. Steinetz)

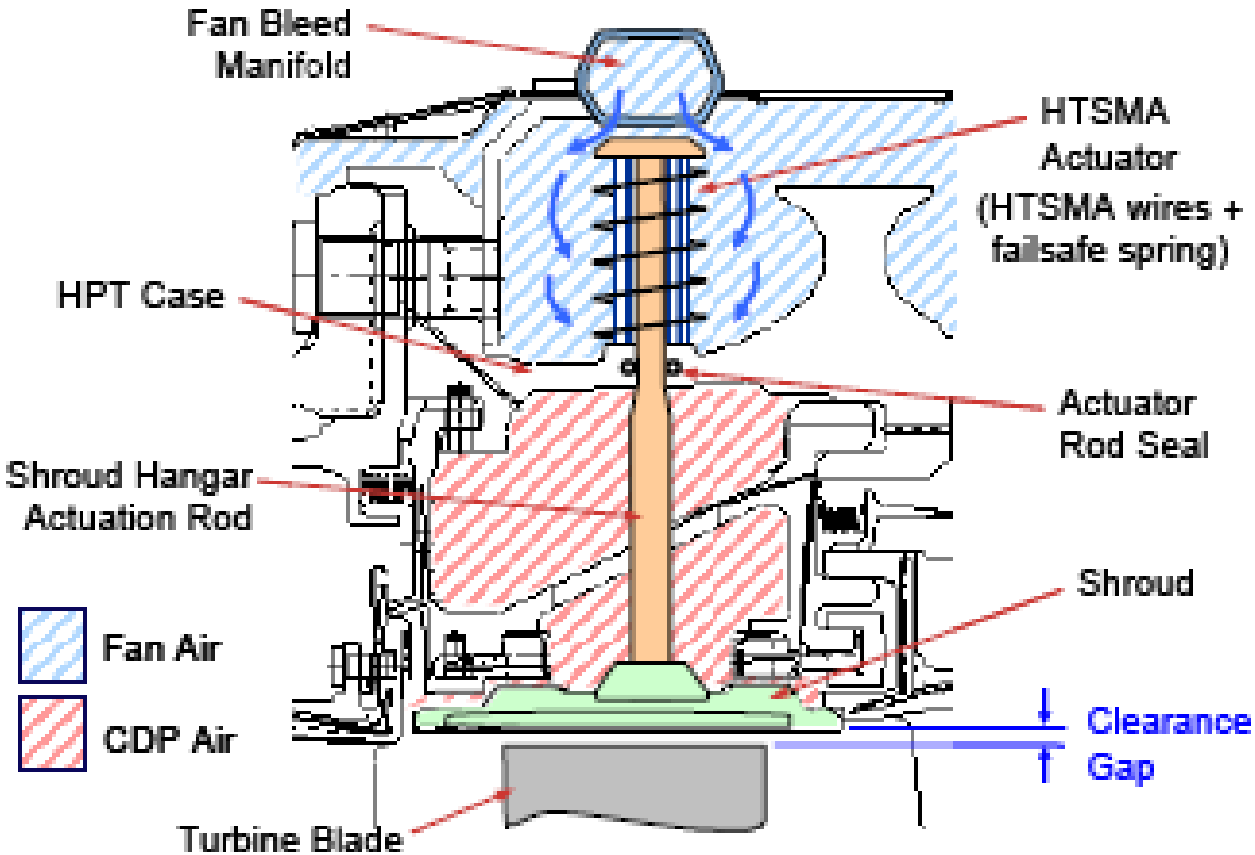
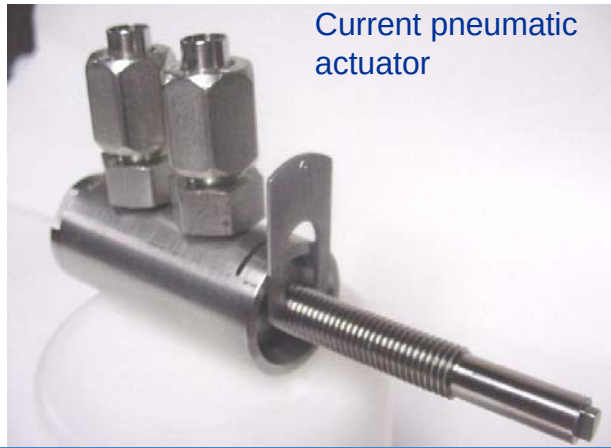


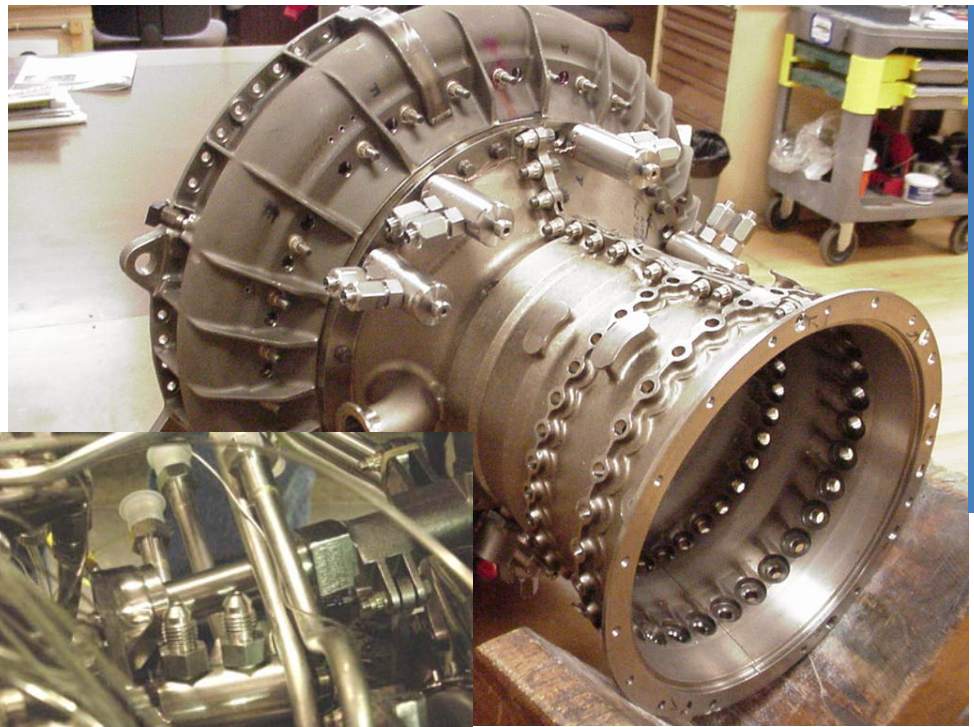
Figure 2: HTSMA active clearance control actuator concept.

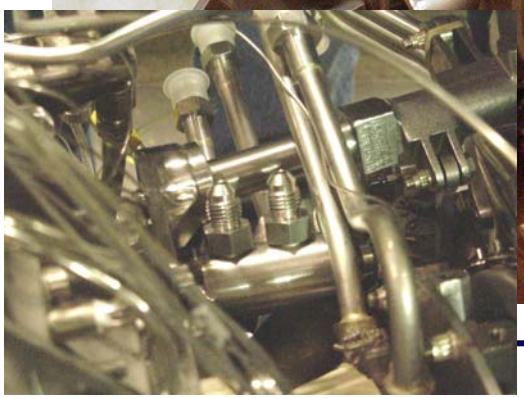
HTSMA actuated Flow Control Rod for T700 Engine

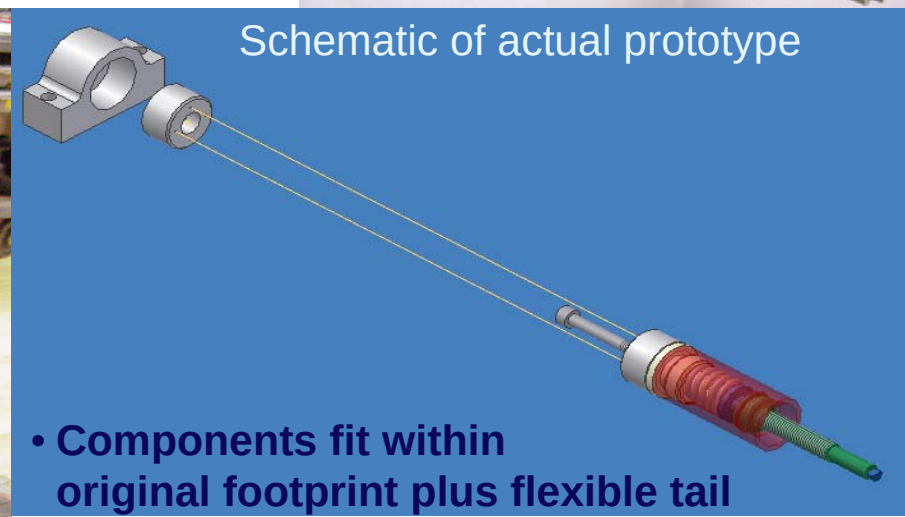
IRD04-40/49

- Goal: design flow control actuator for integration within an operational T700 engine for compressor stability enhancement
- Prototype actuator built using experimental Dynalloy (Ni,Pd)Ti SMA (140 °C capability), similar strain characteristics as new NASA 260 °C NiTi(Pd,Pt) alloy
- 20” flexible device for .25” deflection. Actual needs < .14” deflection.





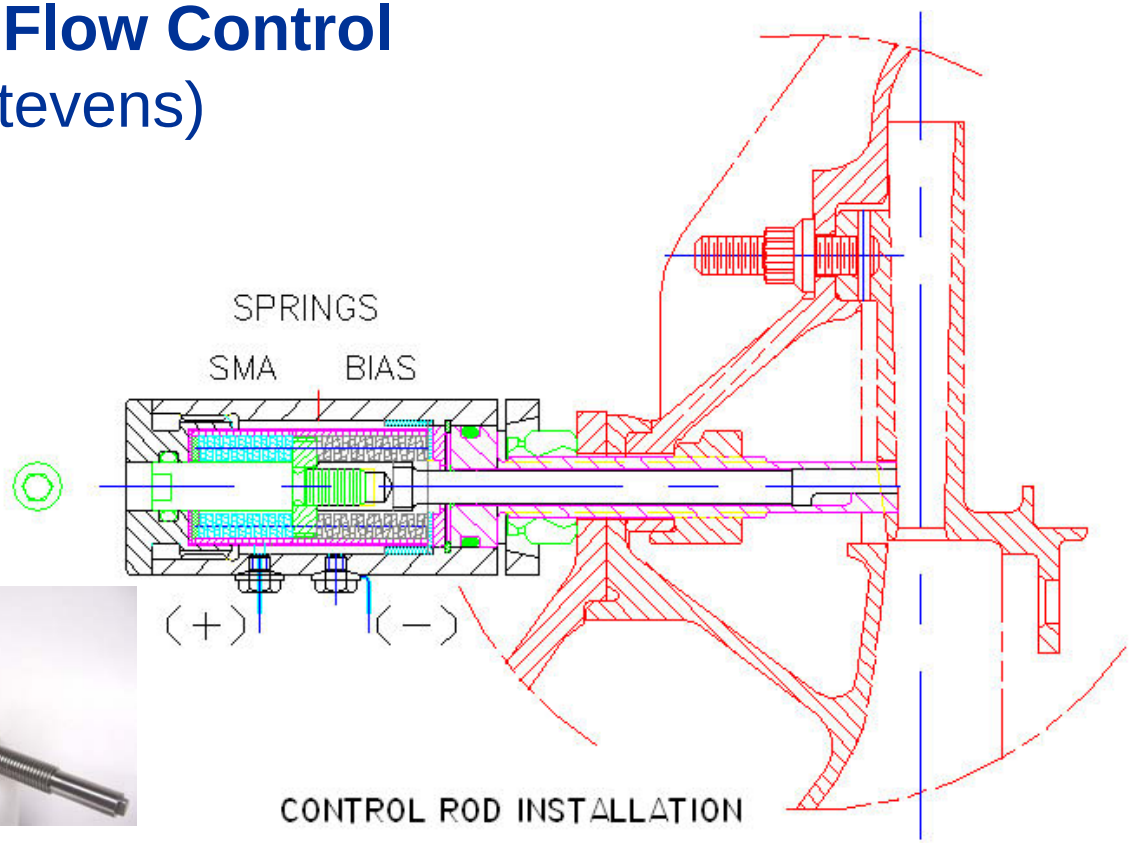




- **Components fit within original footprint plus flexible tail**
- Low power 10 watt
- With proper current & duty cycle 0.3 s actuation time

Advanced HTSMA Linear Actuator For T700 Engine Flow Control

(Mark Stevens)



- Actuator design with opposed biasing springs
- First foray into the development of the materials technology for making a HTSMA springs
  - Shape setting / training
  - Characterization of shear prop.

Summary

- **NASA GRC is actively developing a series of high-temperature versions of commercial shape memory alloys and the advanced processing techniques necessary to produce these new alloys in wire/rod form for use in "adaptive" engine components and high speed morphing structures**

- **A number of applications are already under study and many more are possible**