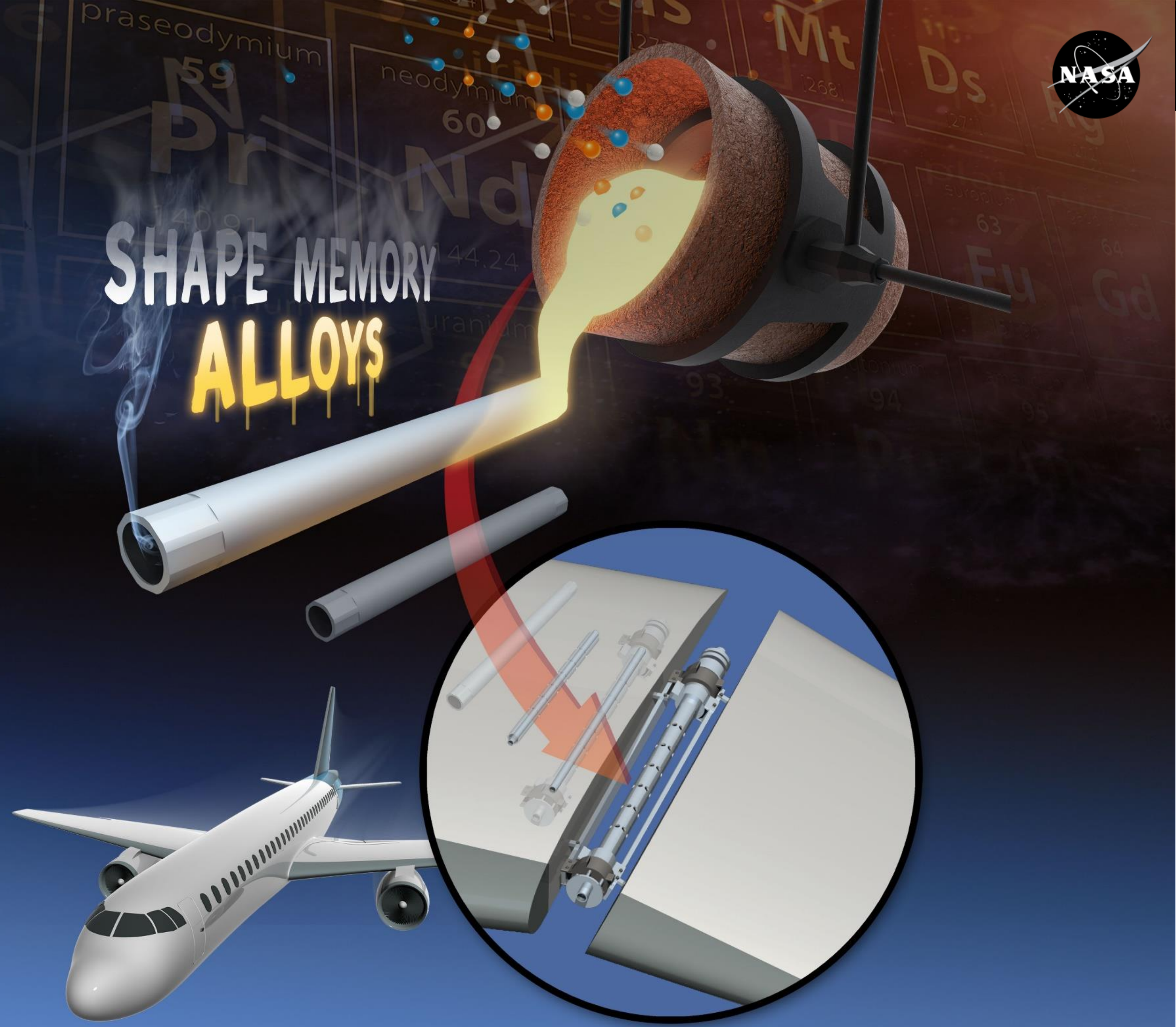
National Aeronautics and Space Administration



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SHAPE MEMORY ALLOYS – NOT YOUR ORDINARY METAL

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NASA Glenn Research Center
U.S.A

May 2020

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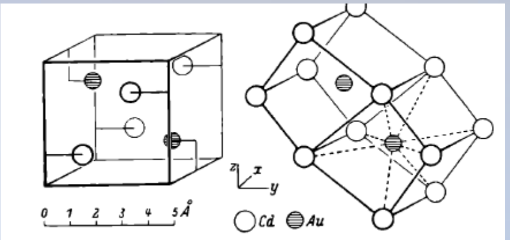
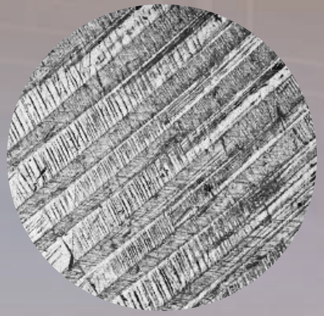
1932

Gustav Arne Ölander[1]
(Swedish chemist)

First discovery of shape memory phenomenon in Au-Cd Alloys



1937



A. Greninger and V. Mooradian[2]
(Harvard University)

Transformation in CuZn and CuSn, first observation of martensite phase disappearance

1949

Kurdjumov and Khandros[3]
(U.S.S.R.)

Martensite transformation is "*Thermoelastic*"—first connotation

1951

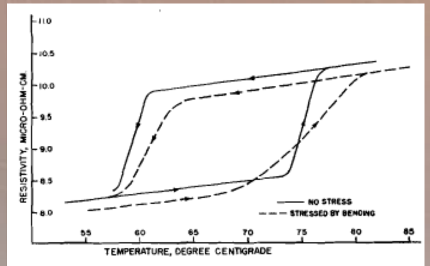


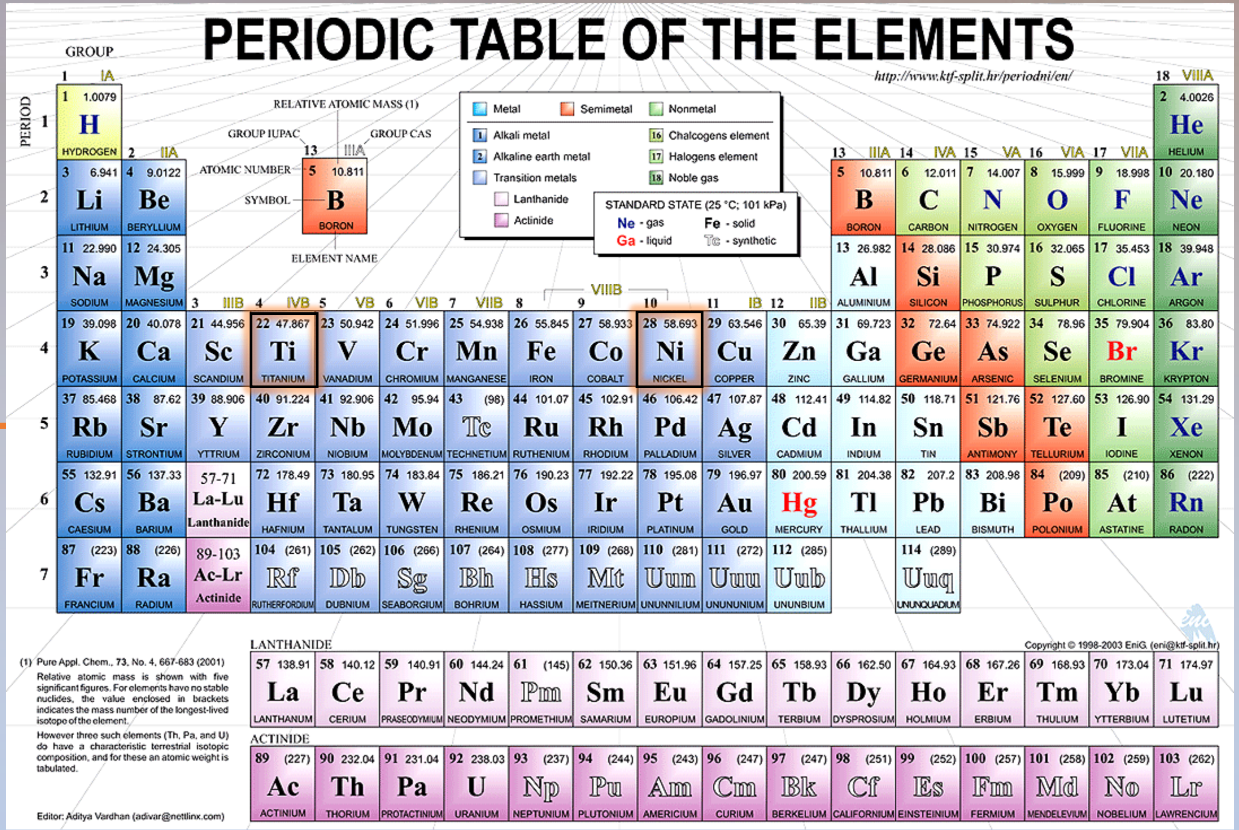
Fig. 1—Resistivity-temperature curve for single crystal Au-Cd alloy containing 47.5 atomic pct Cd.

Chang and Read[4]
(Columbia University)

Diffusionless transformation in Au-Cd
First report of hysteresis curve (resistivity)

William J. Buehler in 1968, pictured with a demonstration of nitinol wire. Electricity was passed through a straight piece of wire, and the wire would change into the word “innovations.” The oak leaf, U.S. Naval ordnance laboratory, White Oak, Maryland, June 1968. [7,9]

1962



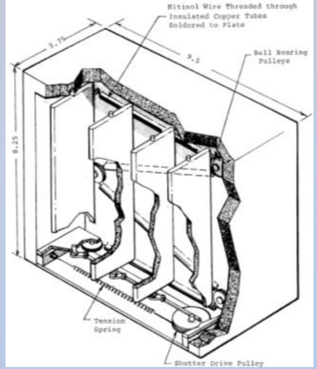
W. J. Buehler[5] and F. Wang[6]
(Naval Ordnance Laboratory)

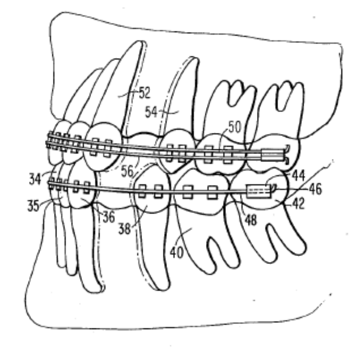
First discovery of shape memory in NiTi alloy

H. Schuerch[10]
(Astro Research Corporation for NASA)

First demonstration of space applications (Nimbus Spacecraft)

1968





U.S. Pat. No. 4,037,324

1969

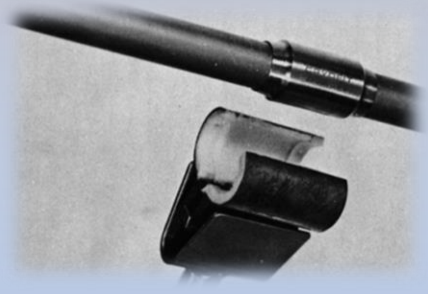
G. Andreasen
(University of Iowa)

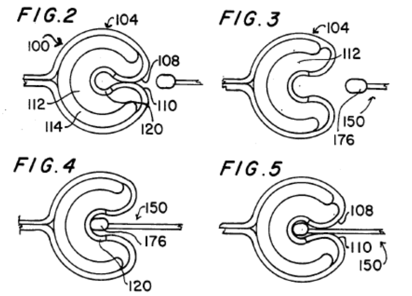
First medical application—orthodontics, *made the first implant of a superelastic orthodontic device (1975)*

J.D. Harrison and D.E. Hodgson[11]
(Raychem Corporation)

First application of NiTi in aerospace (cryofit coupling for F–14)

1970s



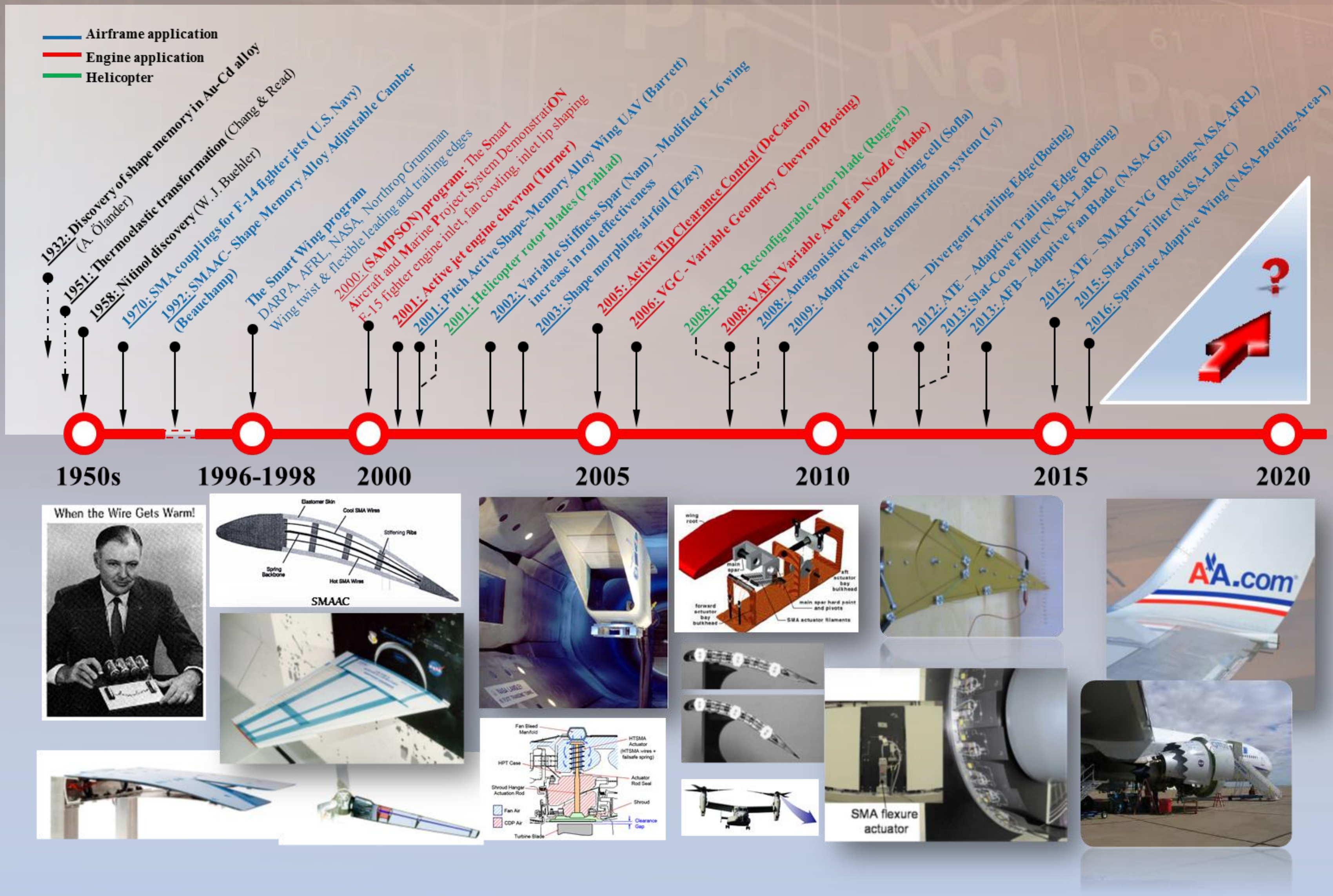


US Pat. No. 4,621,882

1986

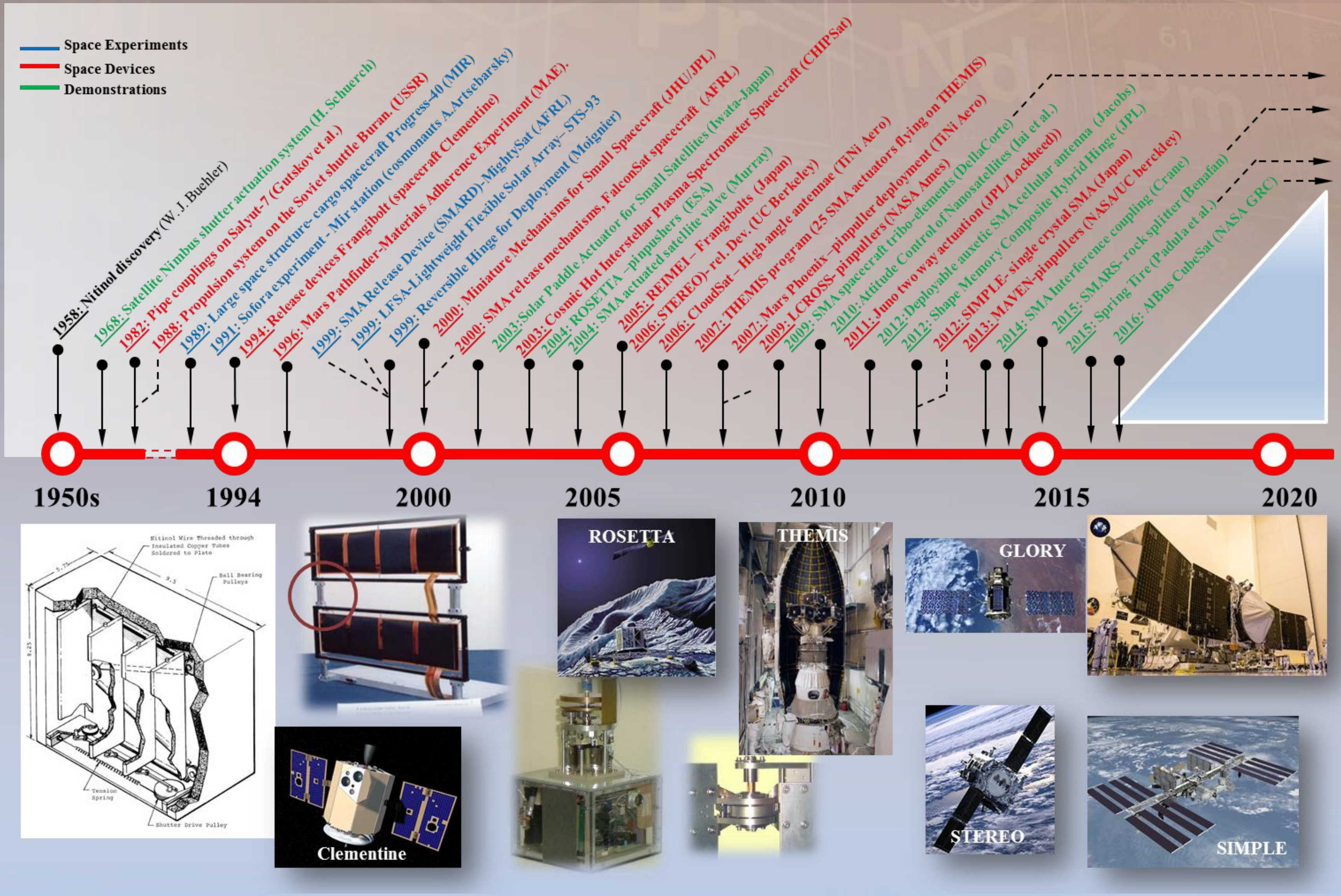
J.F. Krumme[12]
(Beta Phase Inc.)

First SMA actuator in electronics (Thermally responsive electrical connector)



Applications of Shape Memory Alloys in Aeronautics

The first commercial application of SMAs was pipe connectors in a hydraulic system of the F–14 military airplane (by Raychem Corporation[7])



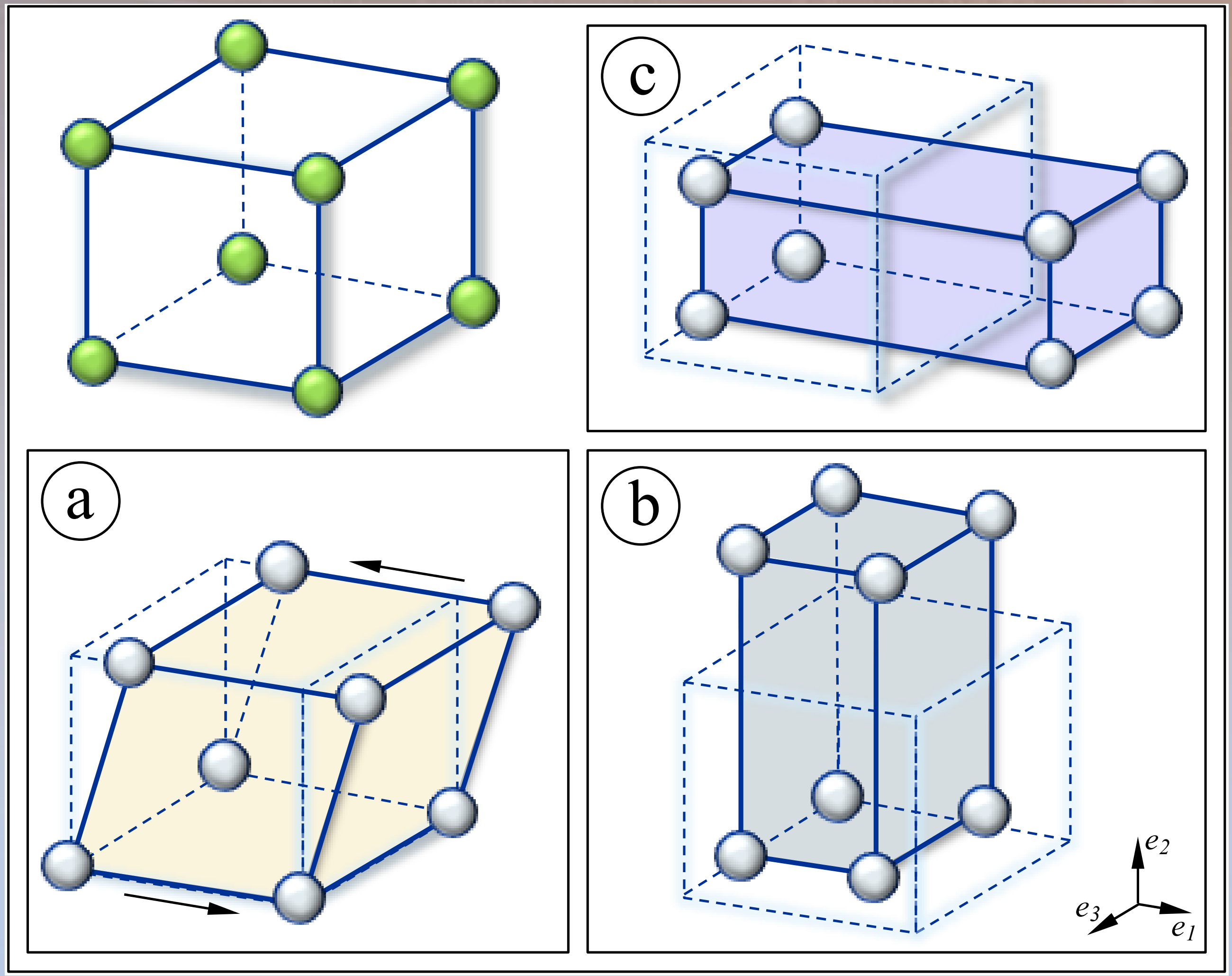
Applications of Shape Memory Alloys in Space

First demonstrations in 1968 using NiTi by Astro Research Corporation for NASA[8]

Shape memory alloys (SMA):

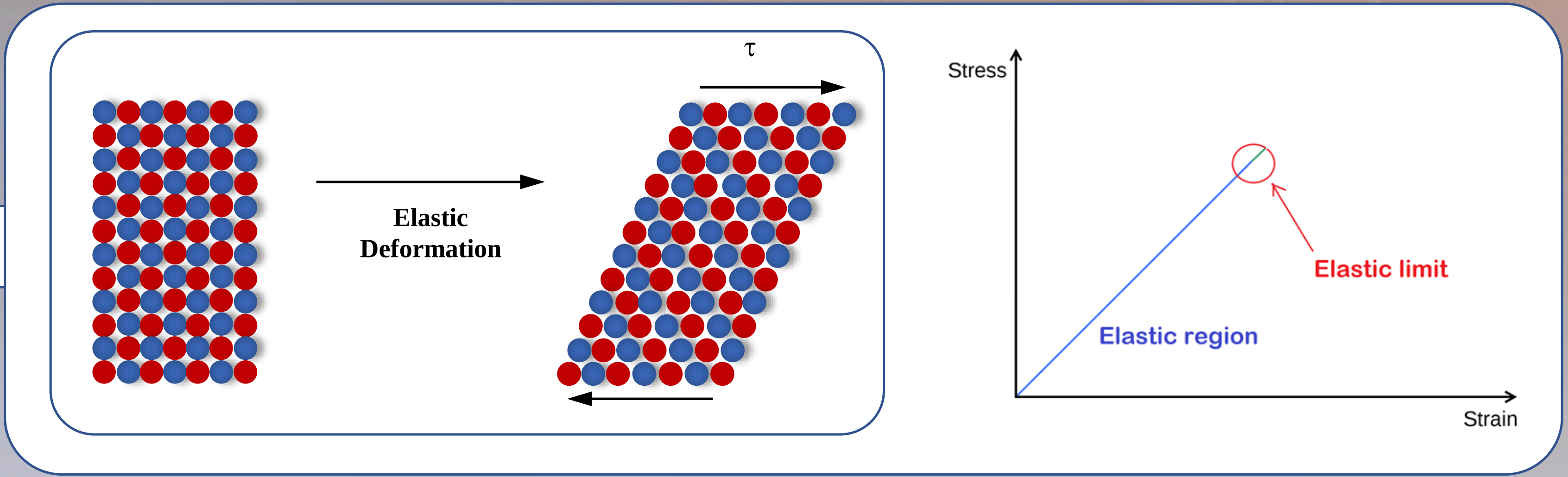
- Alloys that have a "memory." These materials have the ability to remember and recover their original shapes with load or temperature.
- SMAs exhibit a solid-to-solid, reversible phase transformation

Variant selection
(Change in crystal structures)

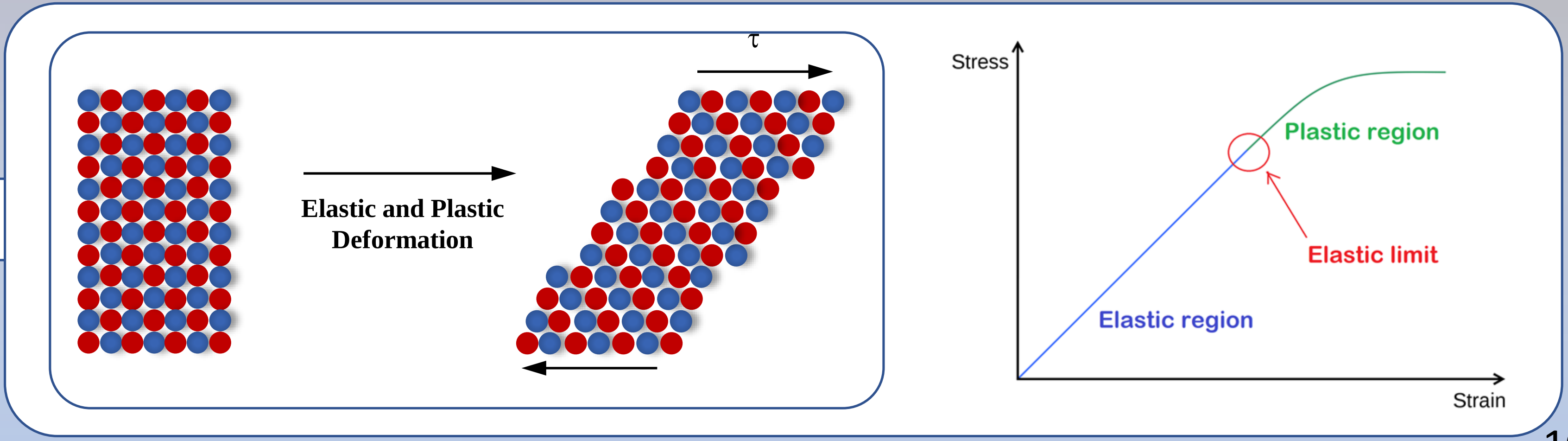


Shape Memory Alloys Conventional Metals

1. Elastic Deformation (REVERSIBLE)

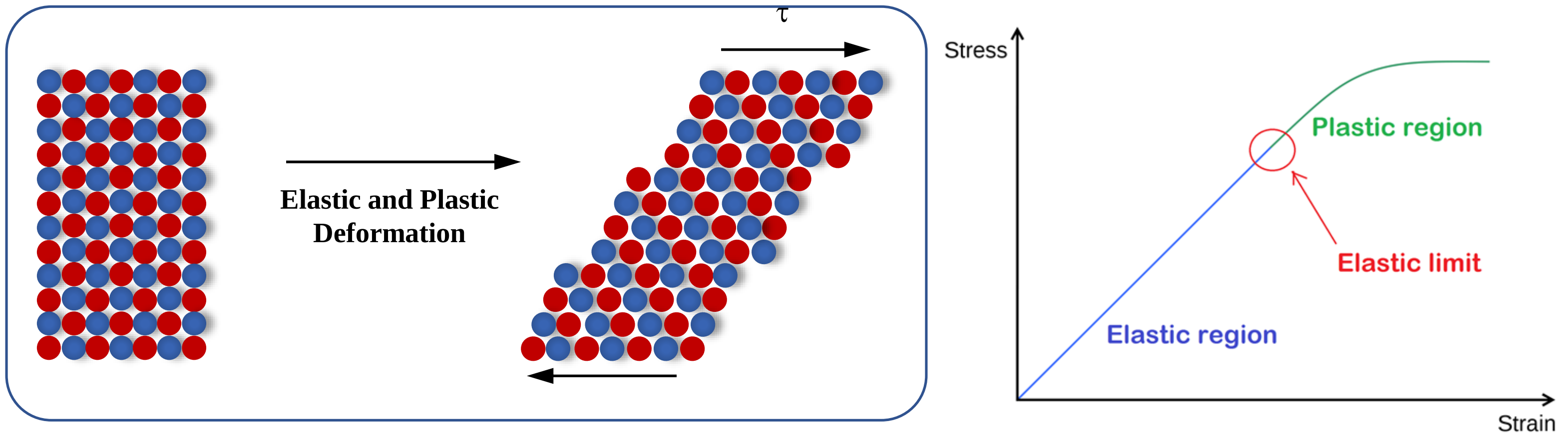


2. Plastic Deformation (PERMANENT)

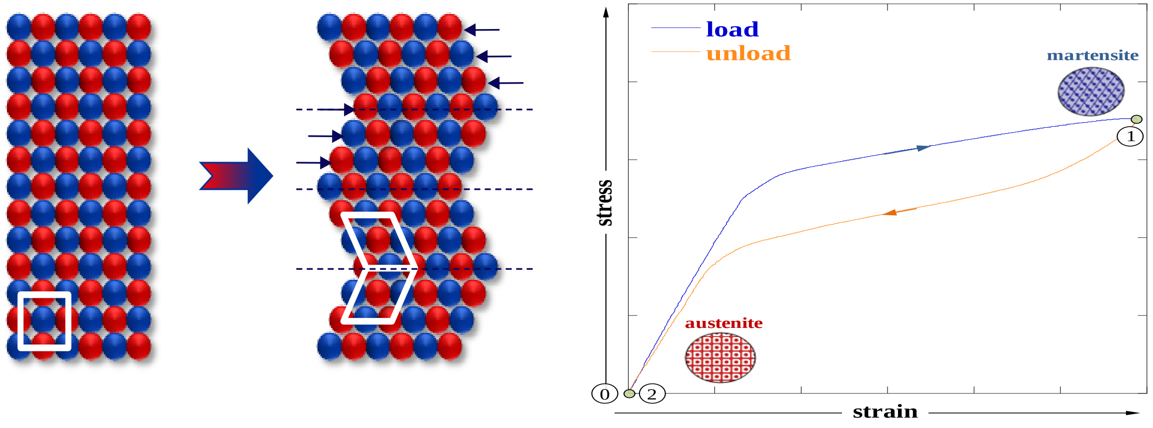


Shape Memory Alloys vs Conventional Metals

2. Plastic Deformation (PERMANENT)



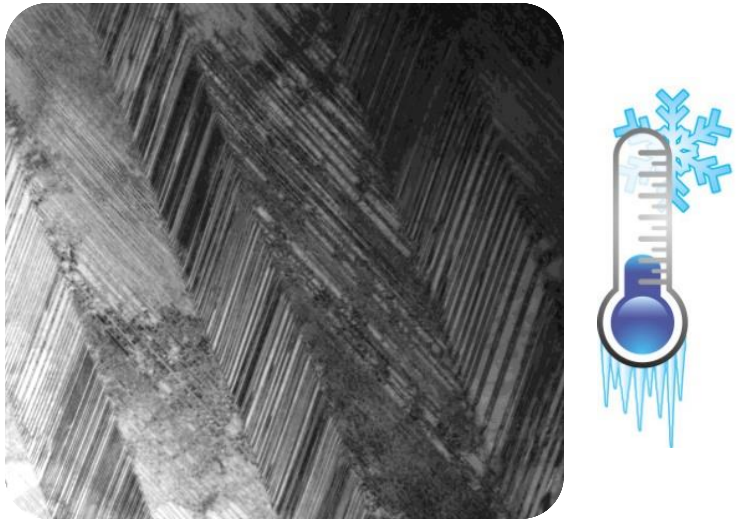
3. Inelastic Deformation (REVERSIBLE)—SMAs



How?

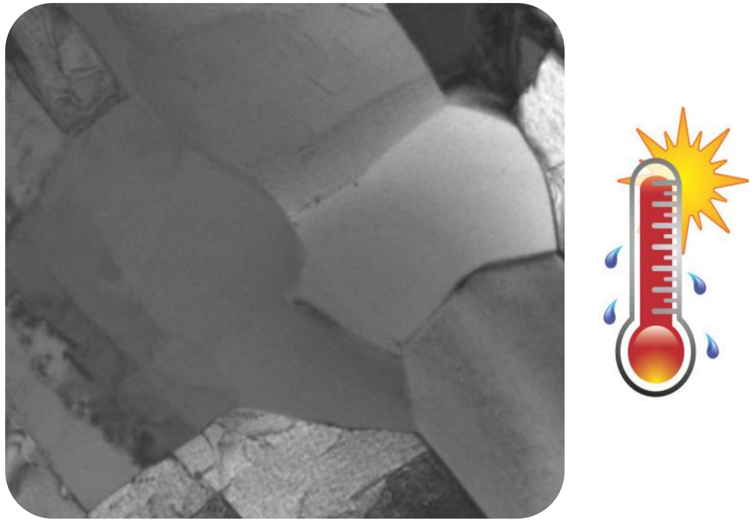
- Twinning
- Bain strain → (lattice deformation)
- Lattice invariant shear → (accommodation)

Cold state:
Also referred to as "*Martensite*"

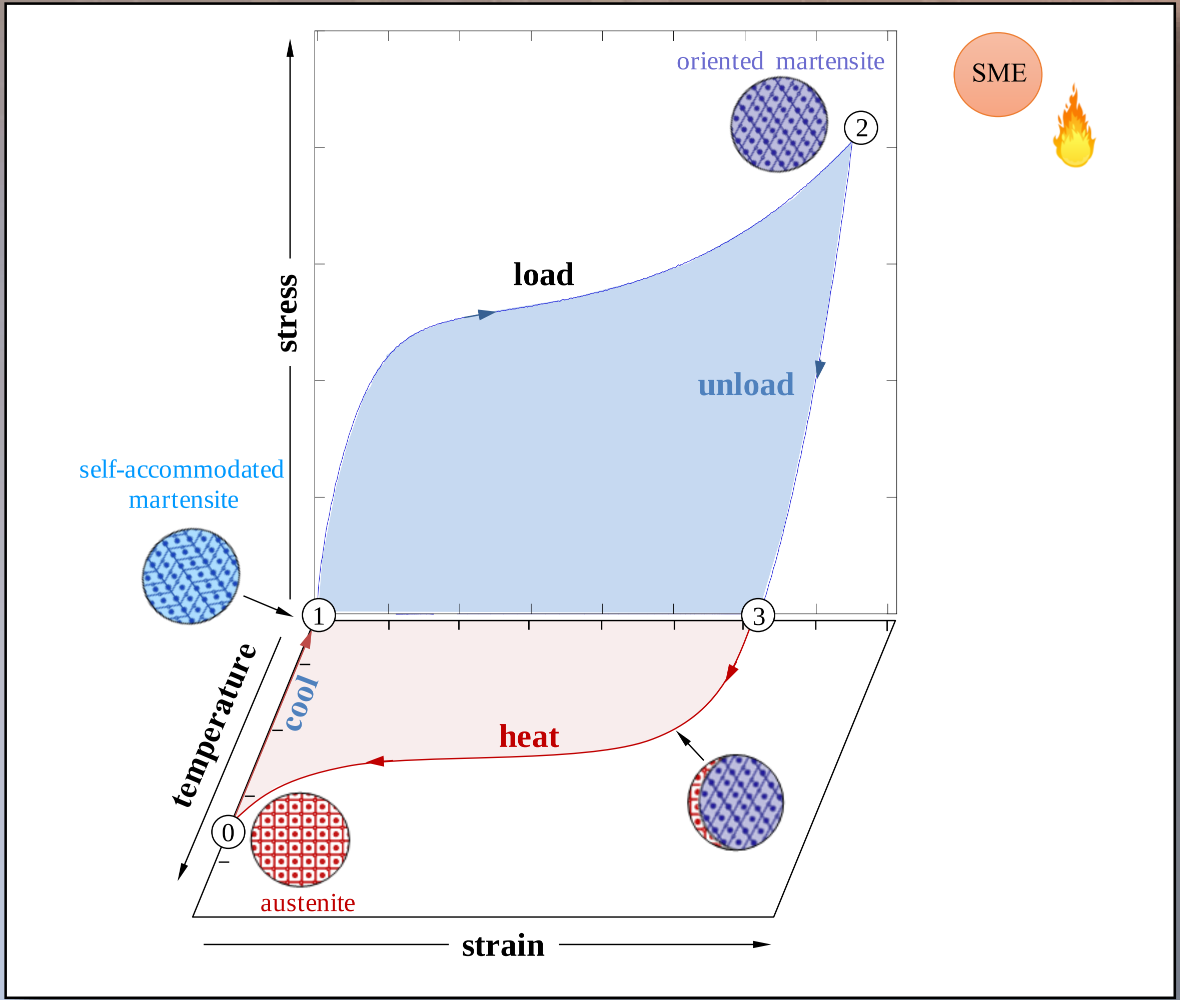


Phase Transformation:
Solid-to-solid, martensitic phase transformation between a high temperature, high symmetry austenite phase (generally cubic) and a lower temperature, low symmetry martensite phase (e.g., monoclinic, tetragonal, ororthorhombic).

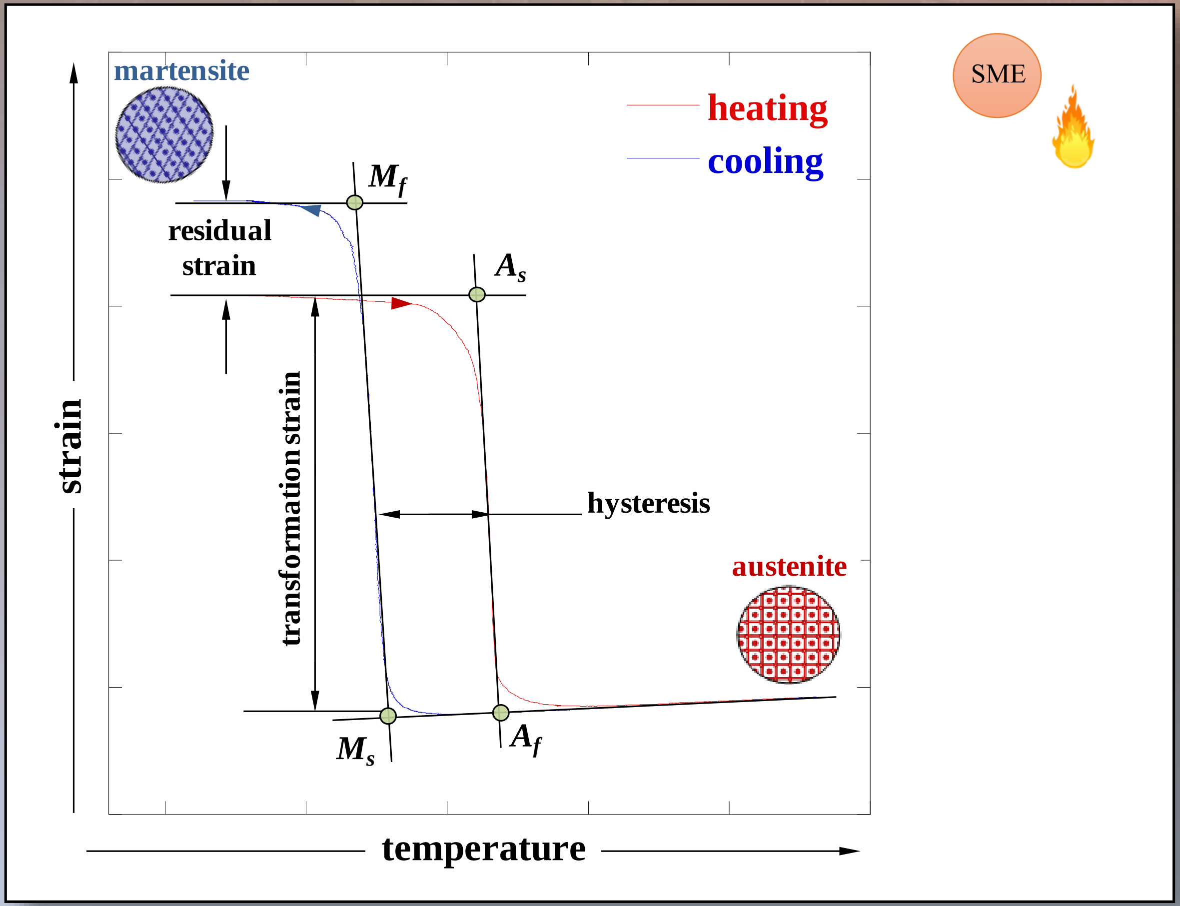
Hot state:
Also referred to as "*Austenite*"



1. ***Shape Memory Effect***
   (Temperature-induced transformation)



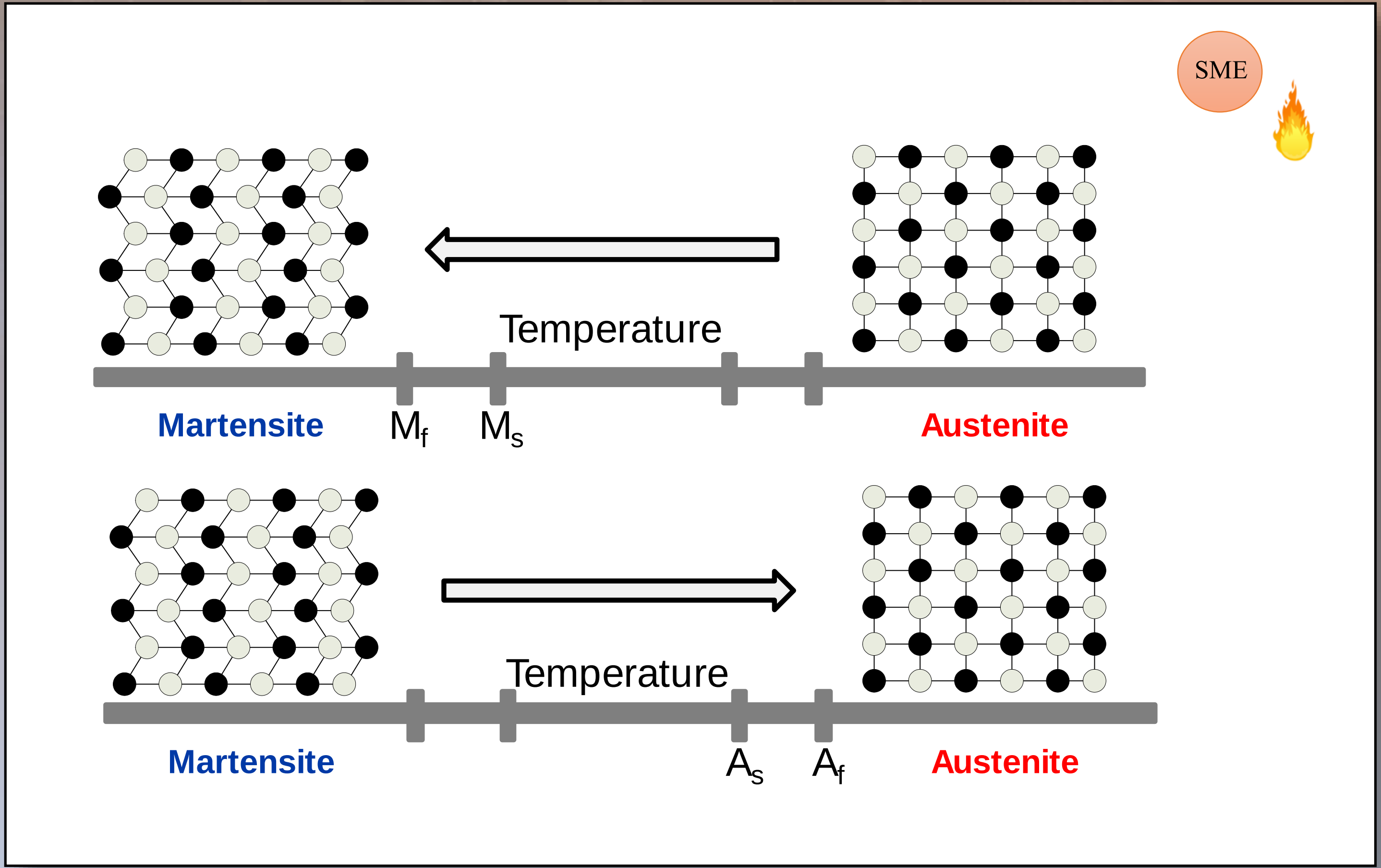
- (0→1): Austenite phase transforms to martensite variants when cooled
- (1→2): Twinned martensite deforms (elastic + reorientation + detwinning (some plasticity may occur))
- (2→3): Unloading (elastic spring back)
- (3→0): Unloading (elastic spring back)



1. ***Shape Memory Effect***
   (Temperature-induced transformation)

- Constant-force thermal cycling (actuator response)
- Determine actuation specific properties (transformation strain, work output, residual, strain, transformation temperatures, and hysteresis)

- On the heating portion, martensite starts to transform to austenite at the austenite start temperature (A_s) and completes transformation at the austenite finish temperature (A_f). During cooling, the forward transformation initiates at the martensitic start temperature (M_s) and finishes at the martensitic finish temperature (M_f).



1. Shape Memory Effect
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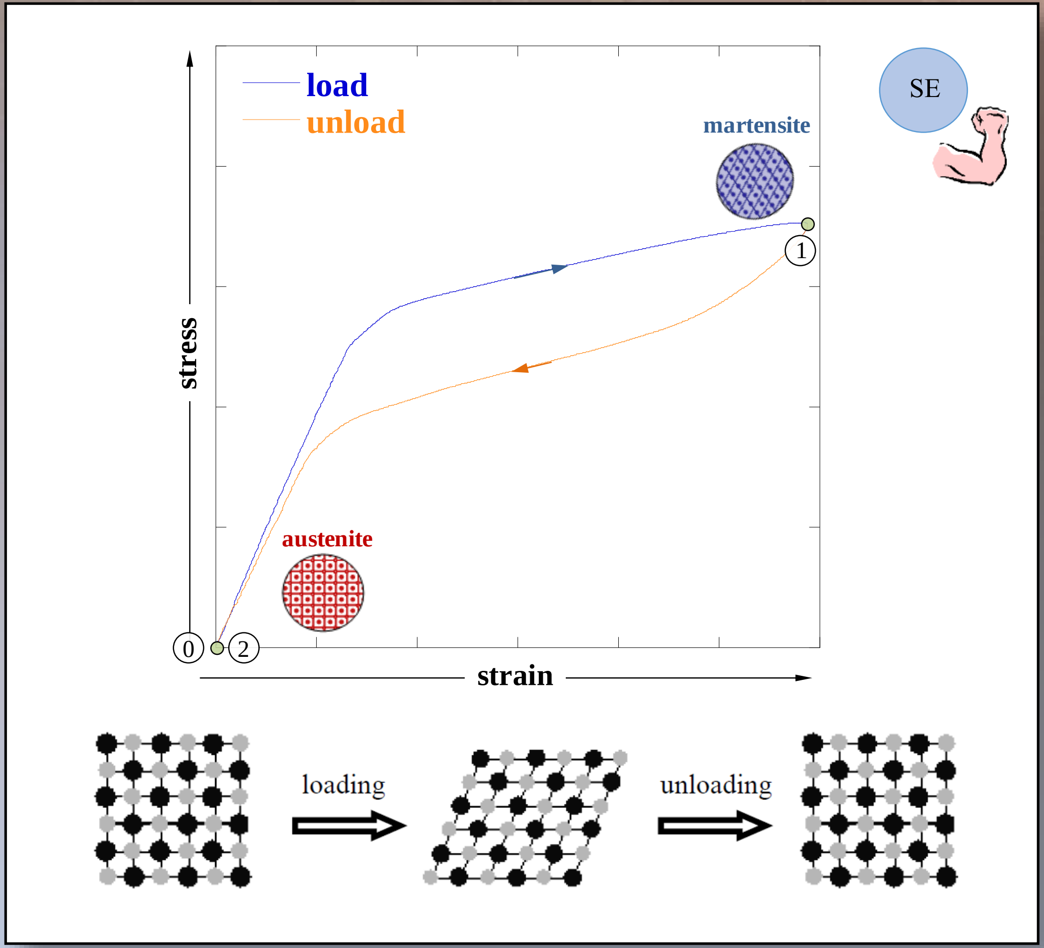
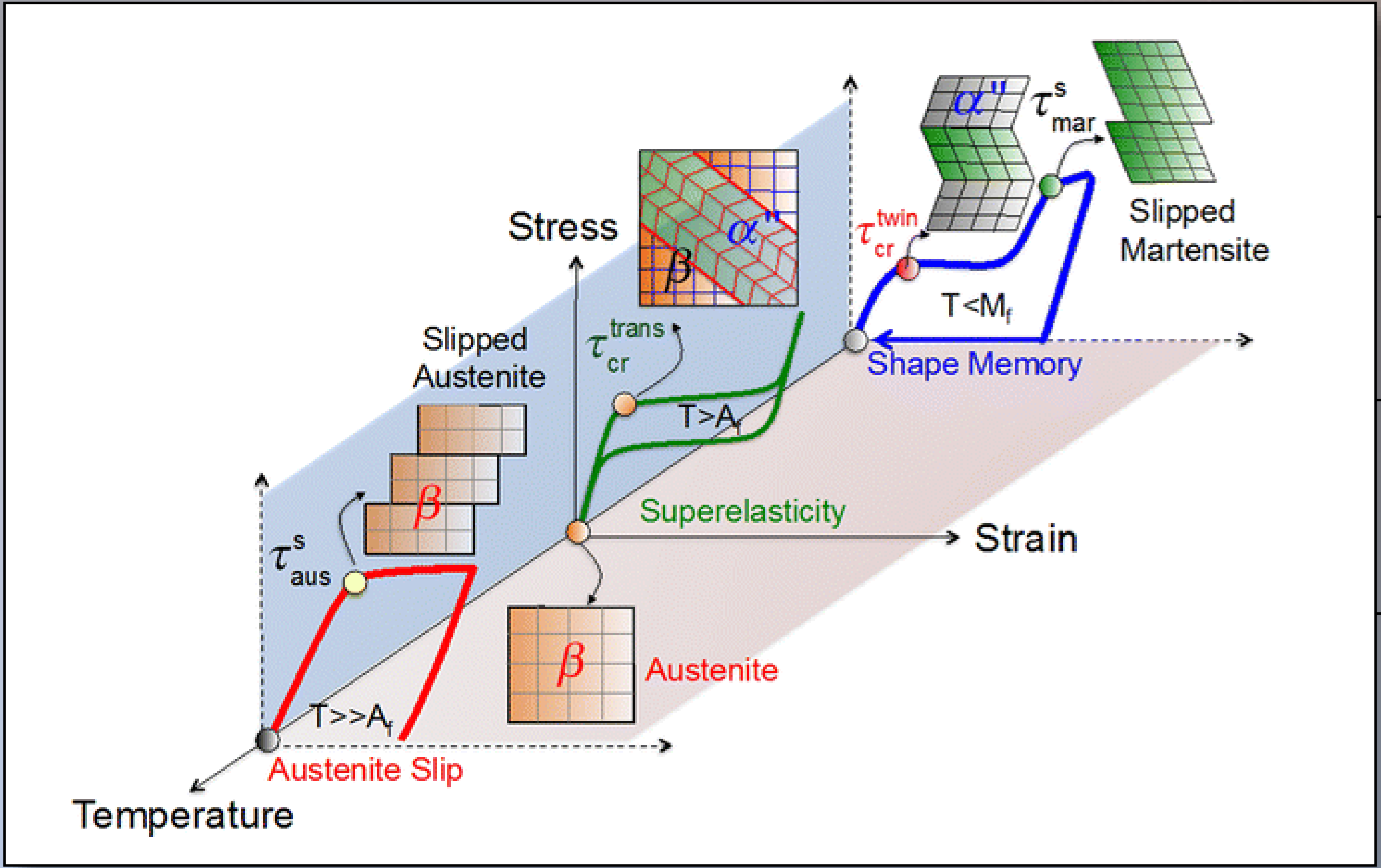
2. Superelasticity/Pseudoelasticity
(Stress/load-induced transformation)



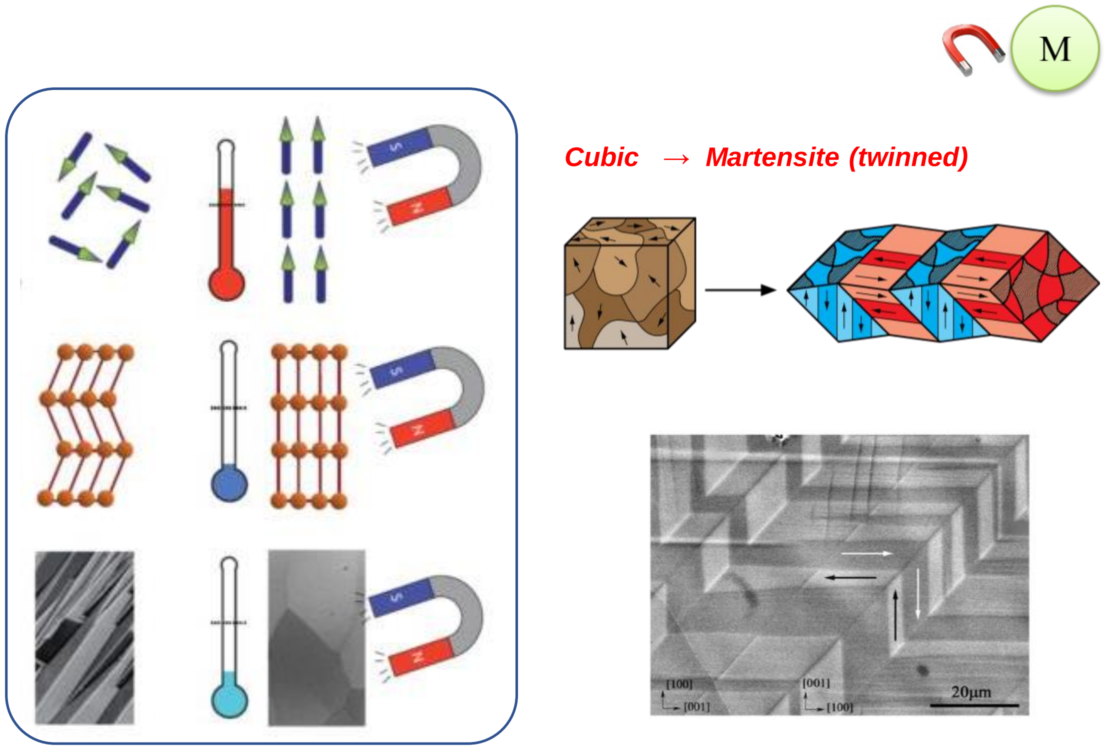
- Strains are generated and recovered mechanically through a reversible stress-induced transformation
- Occurs when deforming some SMAs at temperatures above A_f

Going from: SHAPE MEMORY EFFECT to SUPERELASTICITY to PLASTICITY



- SAME ALLOY
- SAME FORM
- DIFFERENT TEMPERATURE[14]

3. *Magnetic/Ferromagnetic*
(Magnetically-induced transformation)[15, 16]



Ni-Mn-X (X = Ga, Al, In, Sn, …)
Co-Ni-Al
Ni-Fe-Ga

Fe-Pd
Fe-Pt
Co-Ni

- In single crystalline Ni_2MnGa bulk material, strains as large as **10%** have been realized
- Short response times

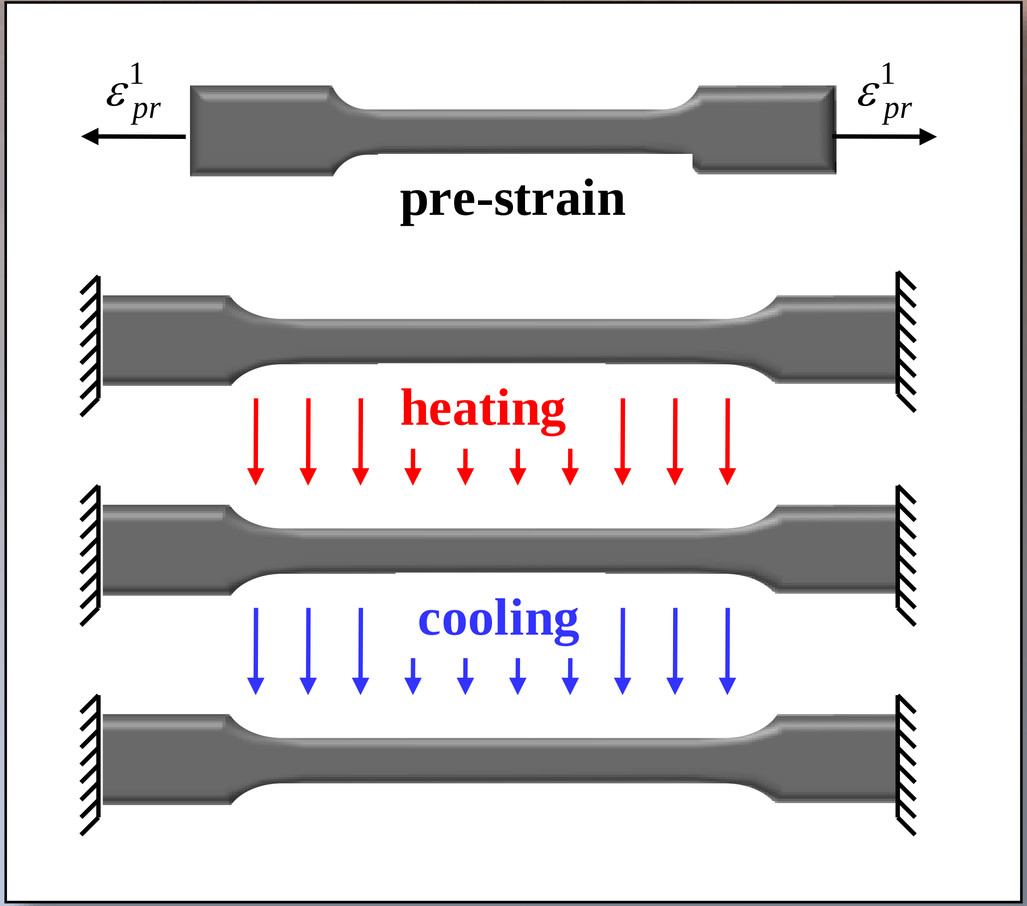
- Minimum magnetic flux density for max strain ~6200 G (0.6 Tesla)

4. Shape-Memory Polymers (SMP)
(Light-induced or electro-active transformation)

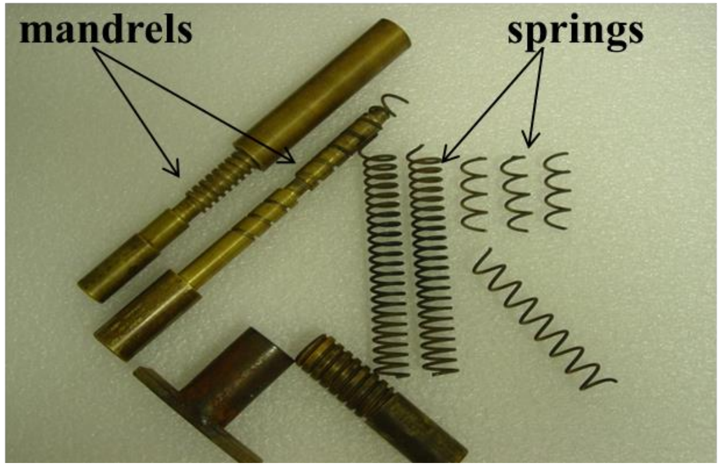
5. Shape-Memory Ceramics (SMC)

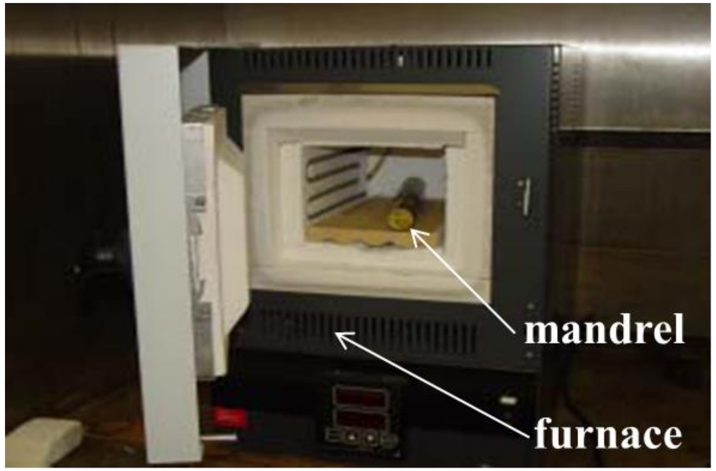
Shape Setting

- Make new forms/shapes
- Procedure:
  1. Pre-strain or deform the raw material (wire, sheet, tube, etc.) in a fixture, die, or mandrel with the desired form
  2. Constrain the material in all directions (displacement and rotation)
  3. Heat treat at some temperature in the proper environment for a certain time (e.g., 450 °C, 5 min, water quench)
  4. Cool the material using a specified cooling procedure
  5. Optimize the final geometry by subsequent shape sets or additional cutting or machining operations



Shape Setting (helical spring example)





Spring fabrication
Coil wire around a solid mandrel with a grooved helical channel

Shape setting
Heat treatment at 500 °C for 25 min., followed by an ice-water quench

Finishing
Electrical Discharge Machining (EDM) to make flat ends.

Actuator: A machine component used to move and/or control a system

Examples: Electric motors

Engines (fuel – gas)

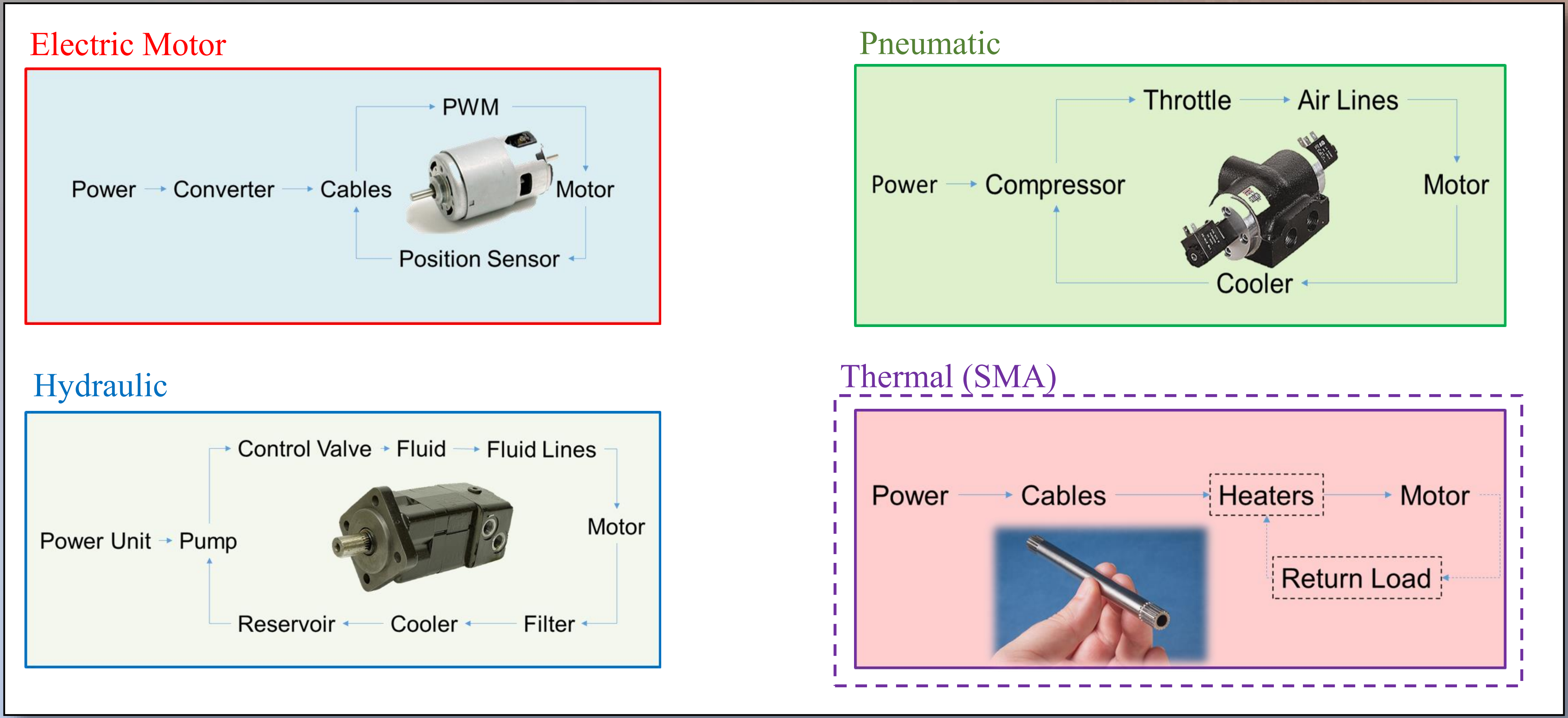
Hydraulics

Pneumatics

Mechanical (rack and pinion)

Thermal (e.g., SMA)

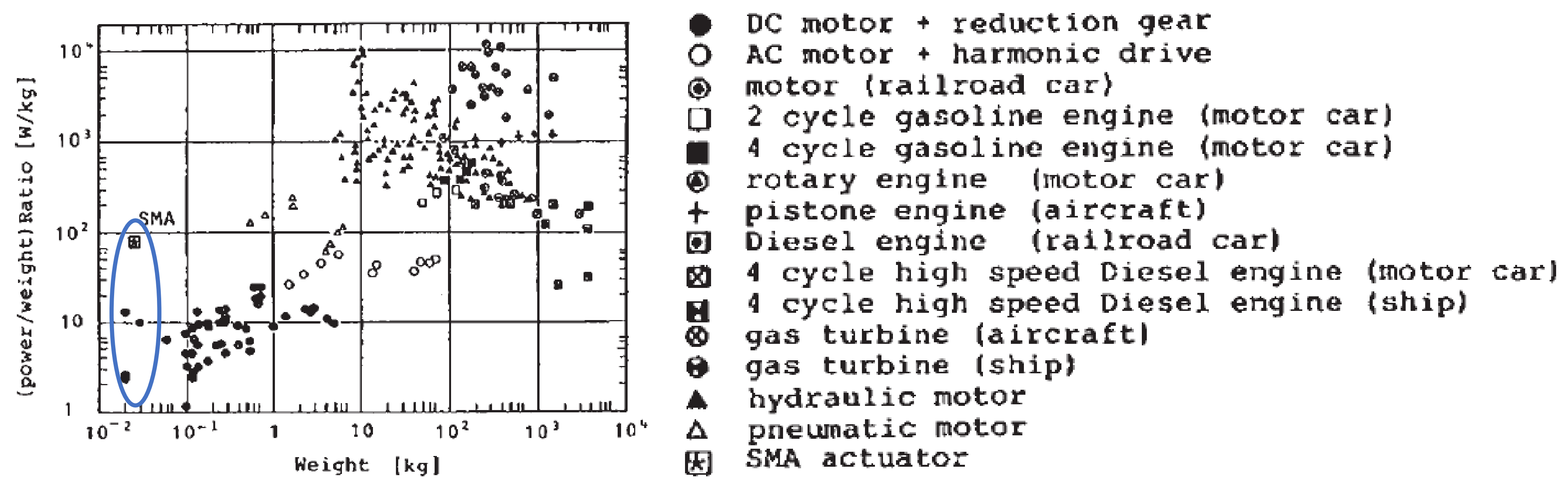
Comparison of a "Simplified" Actuation System (Part Count)



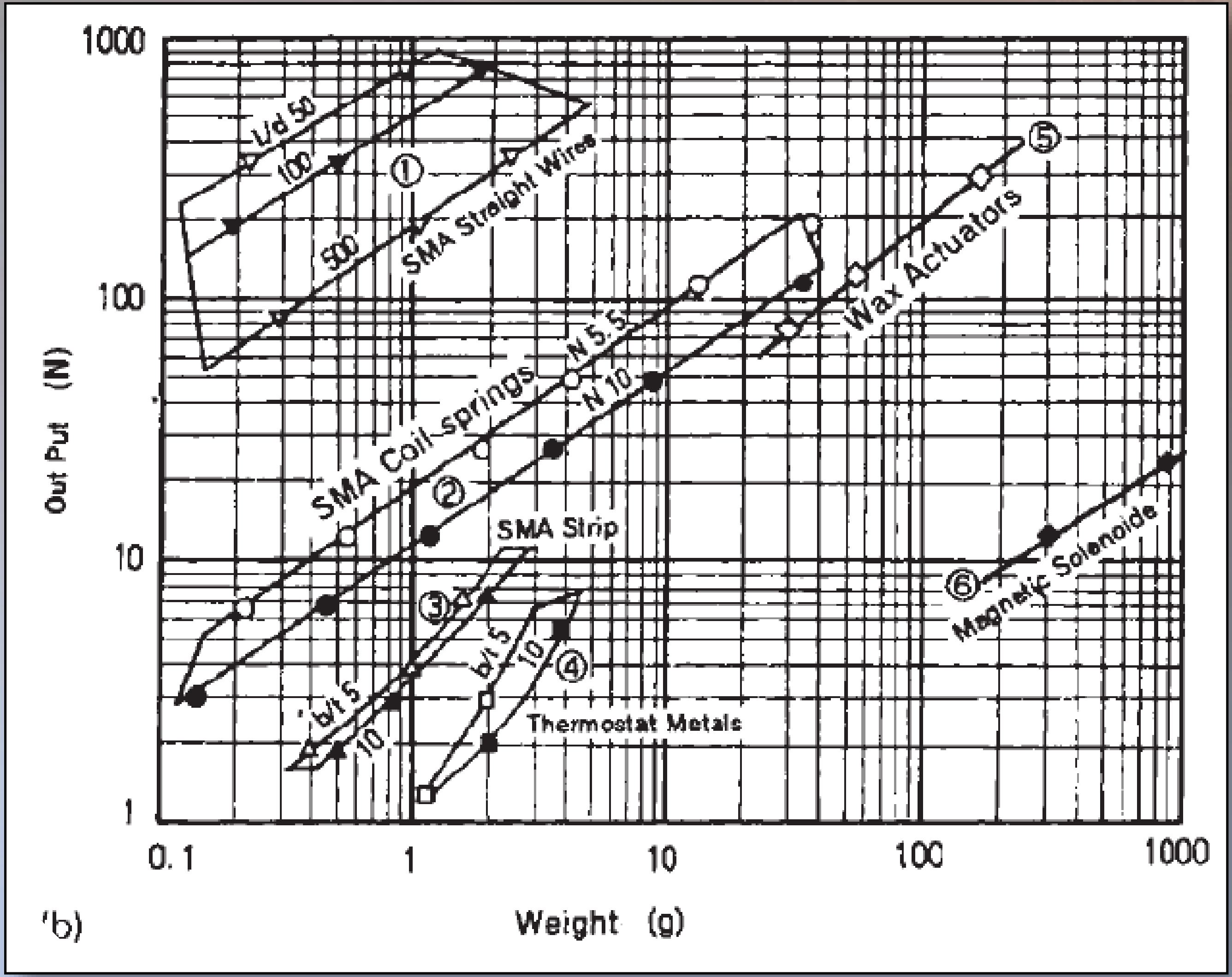
Advantages of SMA-based actuators:

- Reduced complexity (fewer part count, cost)
- Compact form (smaller footprint, package)
- Lightweight
- Silent operation
- Sensor and actuator in a single element
- High power/weight and stroke/weight ratios
- Clean, debris-less, spark-free operation (for high risk application)
- No electro-magnetic interference (EMI) (if not magnetic SMA)
- Flexibility in design integration
- Remember: Inelastic reversibility = large deformation

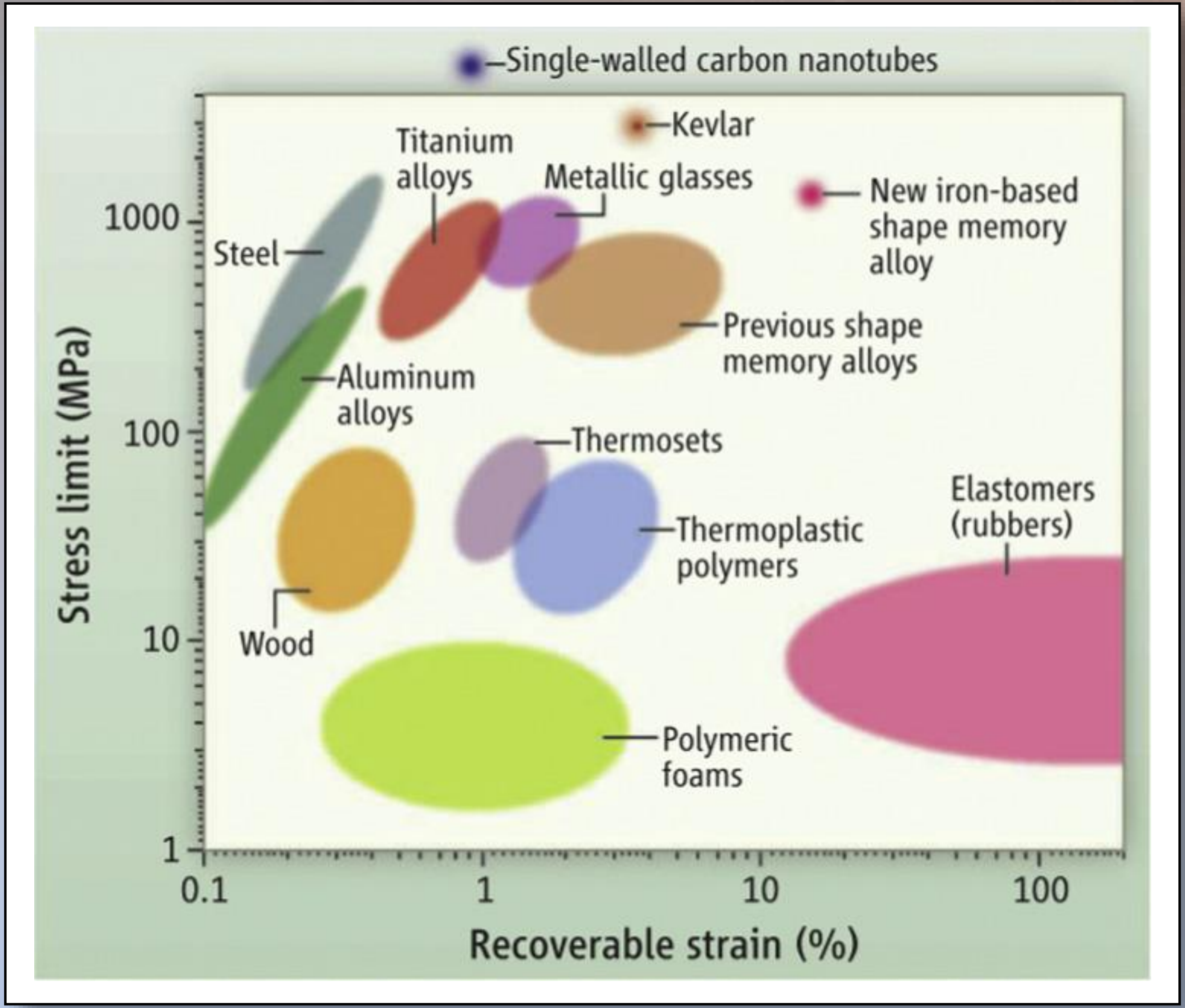
Weight/power comparison[17]



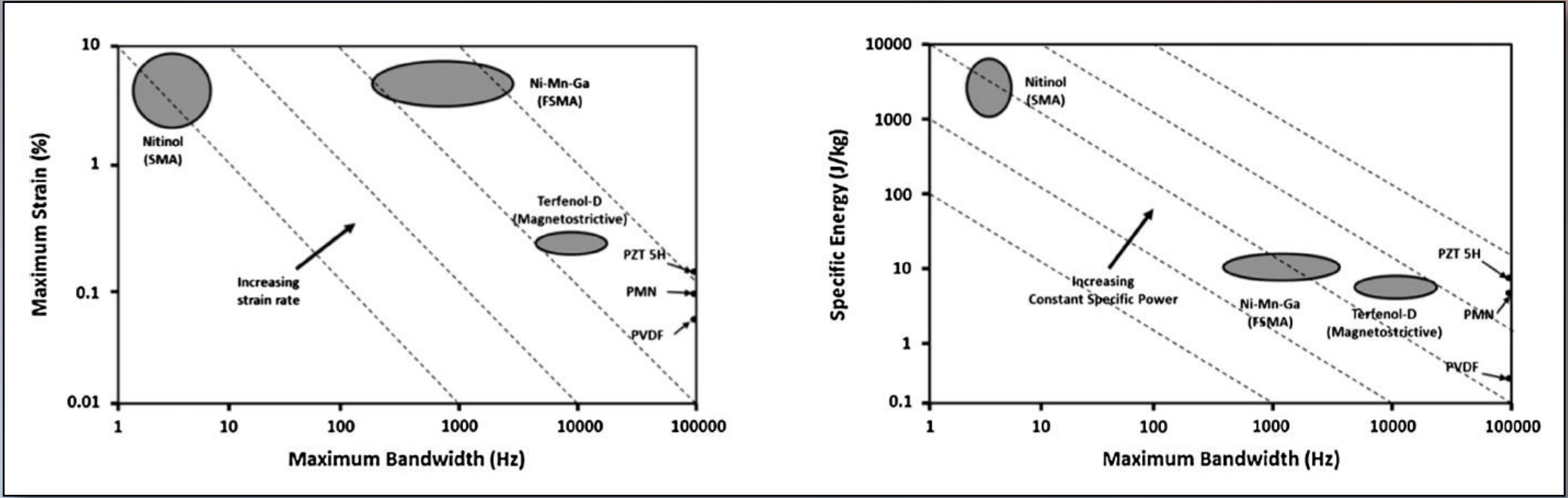
Weight/output comparison[18]



Stress-Strain comparison[19-21]



Bandwidth comparison[20]



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GET TO KNOW YOUR SPRINGS

(Group exercise)

1. From the provided springs, identify:
   - Superelastic spring
   - Shape memory effect spring
   - Two-phase region spring
   - Low-temperature activation spring

2. Make your own spring, "Shape setting":
   - Form a spring on the given mandrel
   - What temperature and time should be used? Why?
   - Try different shape setting temperatures

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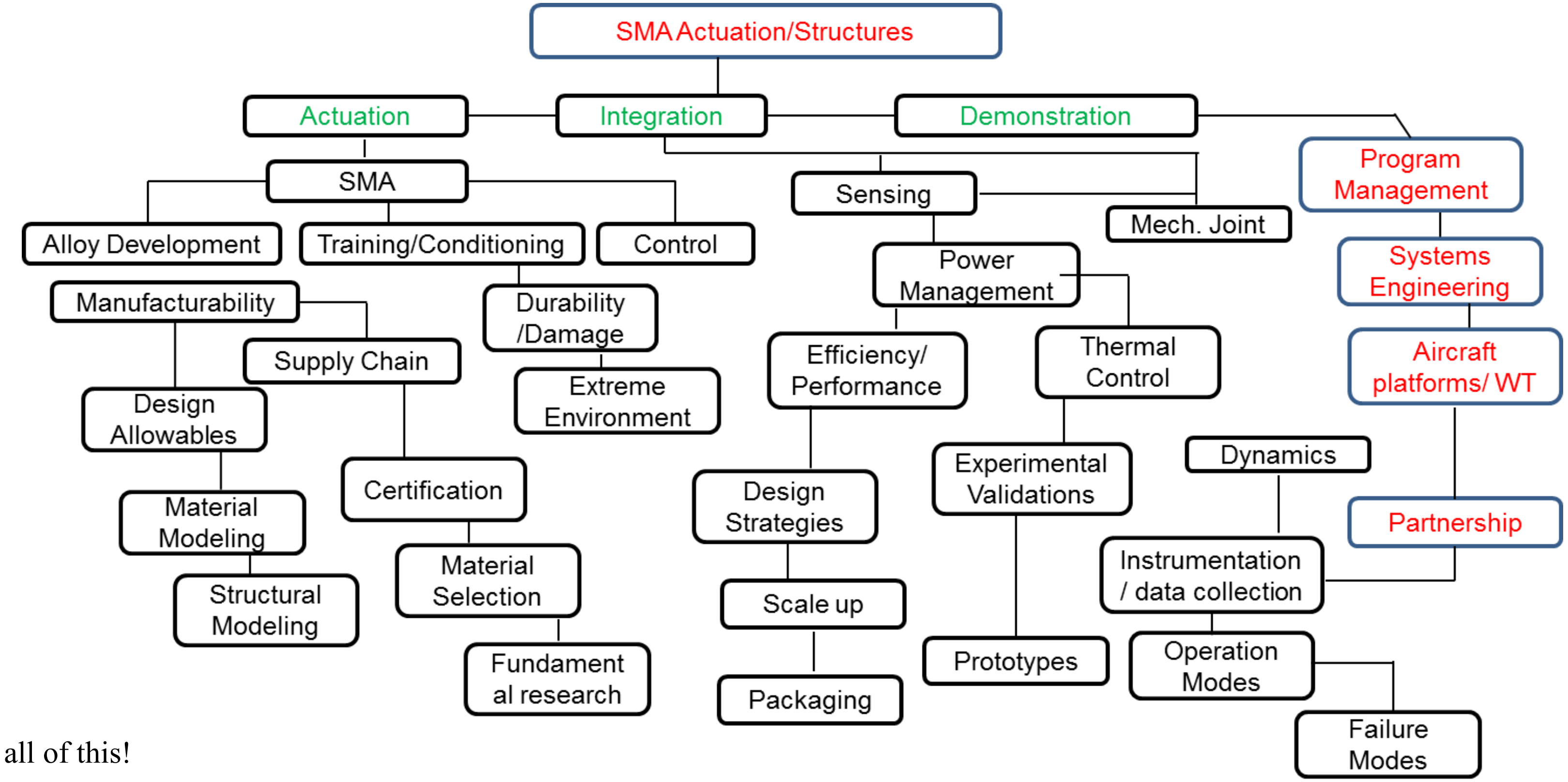


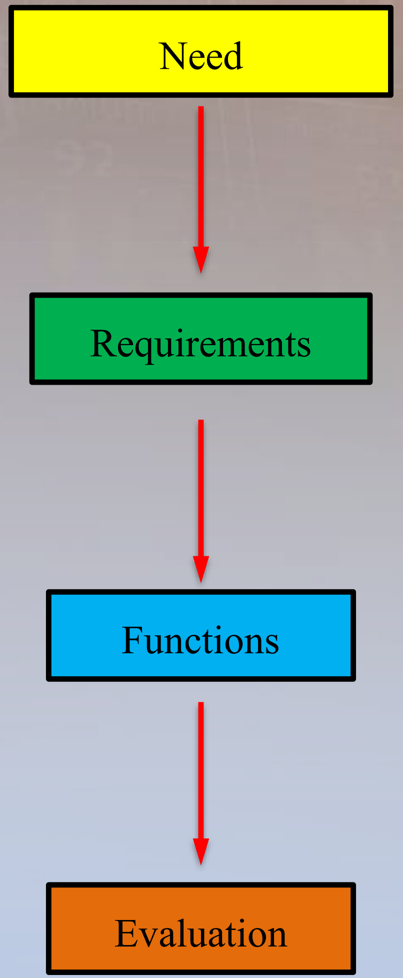
It is simple, just solve all of this!

- **Define Engineering Requirement(s):**
  - ❑ System: mass, footprint, environments, integration, risk…
  - ❑ Interfaces: structural to thermal to electrical to…
  - ❑ Component: functions, pitfalls, supply chain, kinematics, fabrication, analyses (static, dynamic)…
  - ❑ Material: durability, strength, form, surface protection

SMA constraints and requirements

Need to define:

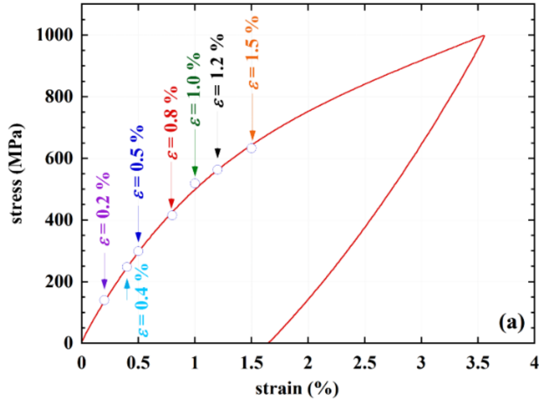
- Type of motion: linear, rotary…
- Required output: force, displacement, torque, bending…
- Available energy source (directed power, collected power)
- Transition temperatures
- Form factor (footprint, weight, packaging, interfaces)
- Actuation time
- Control scheme: e.g., two state system, multi-step actuation…
- Cycle count
- Others: efficiency, cost, manufacturing, energy density…



Bound the design space

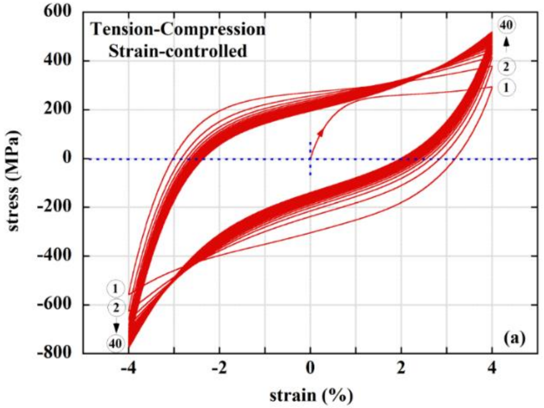
Additional variables with SMAs

Isothermal monotonic



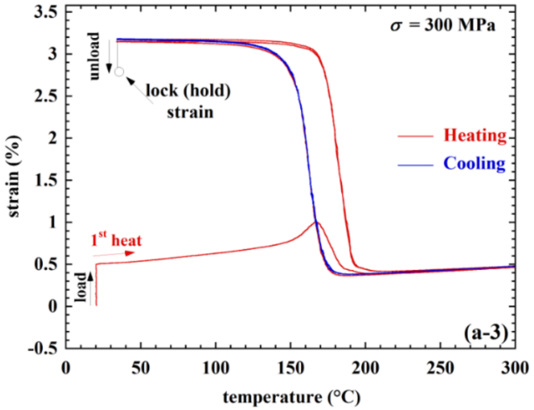
(Elastic moduli, yield, UTS, ductility…)

Isothermal cyclic



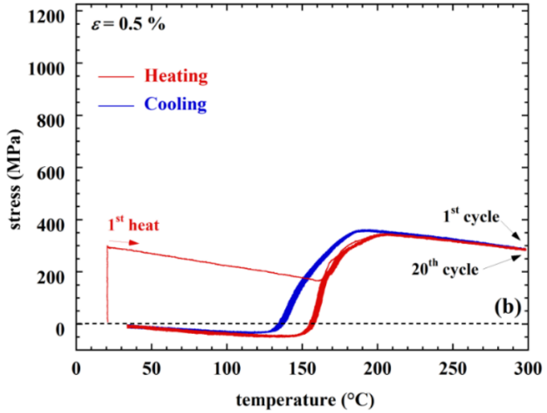
(Reversal, amplitudes…)

Isobaric

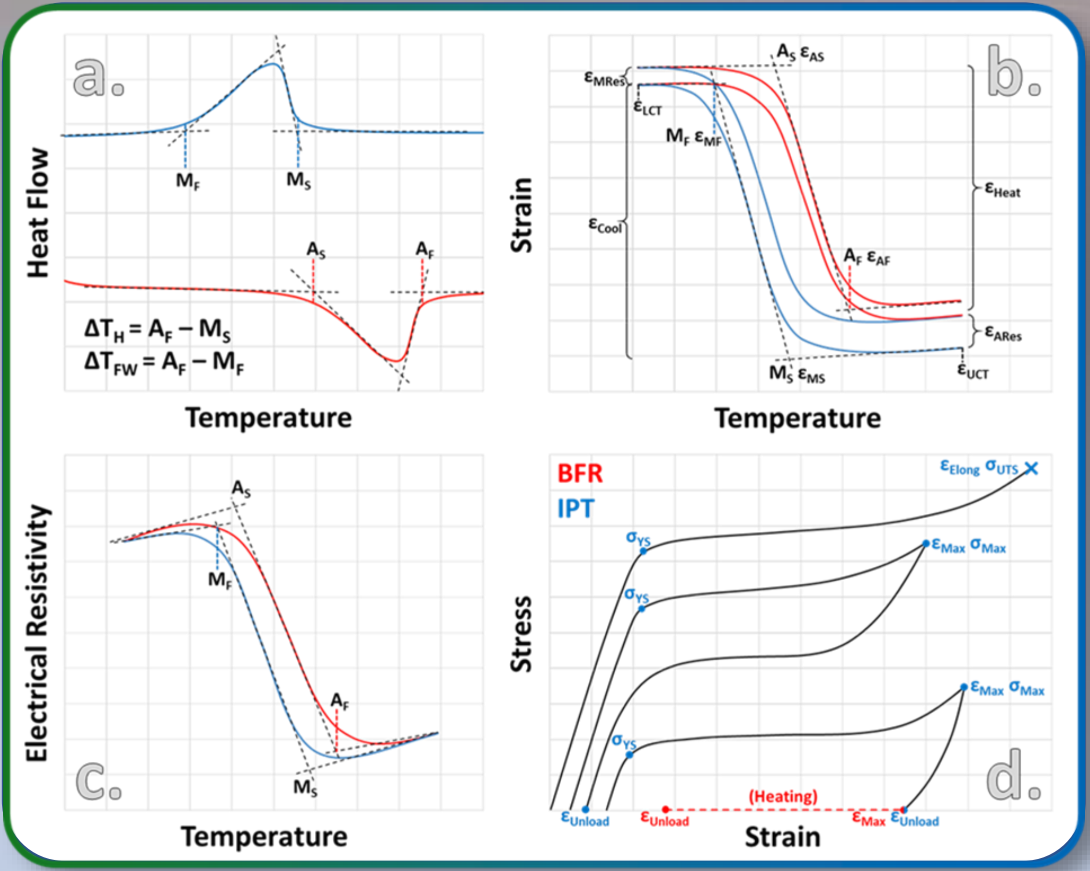


(Strokes, activation temperatures, hysteresis, work output…)

Isostrain



(Blocking forces, jam loads…)



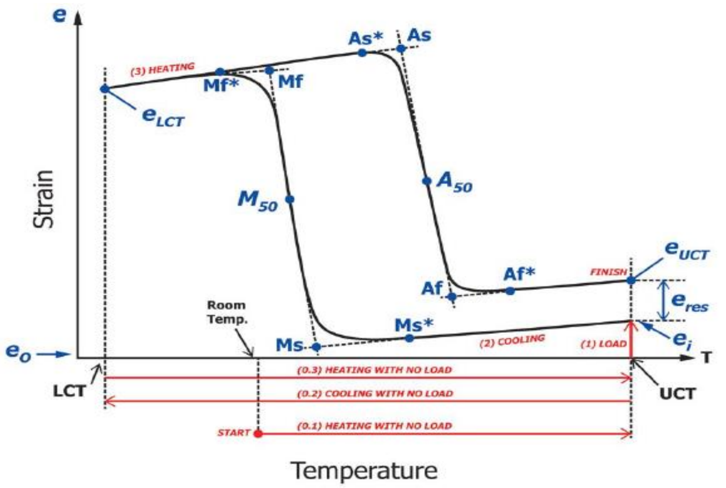
a) **Thermal response**: typically obtained using differential scanning calorimetry (DSC). Measure transformation temperatures, hysteresis, enthalpy…
(under no stress)

b) **Isobaric response**: typically obtained using thermomechanical load frames. Measure stroke, rotation, strains, loads, torques, stresses, work input, load effect on transformation temperatures…

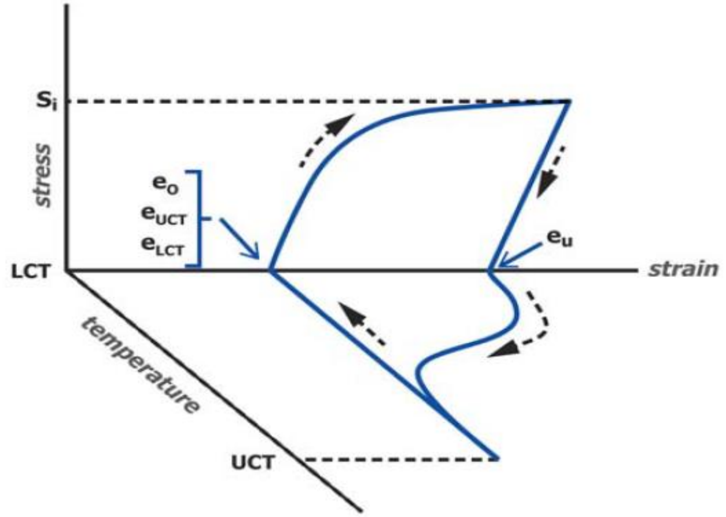
c) **Resistivity**: typically done using a current input. Measure electrical resistance, ideal for sensing applications…

d) **Isothermal response**: typically obtained using thermomechanical load frames. Measure moduli, ductility, superelastic behaviour, reversibility…

Property Name	Nom.	Units
Austenite start temperature	A_S	°C
Austenite finish temperature	A_F	°C
Martensite start temperature	M_S	°C
Martensite finish temperature	M_F	°C
Hysteresis (A_F - M_S)	ΔT_H	°C
Full width (A_F - M_F)	ΔT_{FW}	°C
Yield strength	σ_{YS}	MPa
Maximum-strain/elongation	$\varepsilon_{Max}/\varepsilon_{Elong}$	%
Maximum-stress/UTS	$\sigma_{Max}/\sigma_{UTS}$	MPa
Unloading strain	ε_{Unload}	%
Austenite start strain	ε_{AS}	%
Austenite finish strain	ε_{AF}	%
Martensite start strain	ε_{MS}	%
Martensite finish strain	ε_{MF}	%
Austenite slope	n/a	%/°C
Transformation slope	n/a	%/°C
Martensite slope	n/a	%/°C
Cooling trans. strain (ε_{MF} - ε_{MS})	ε_{Cool}	%
Heating trans. strain (ε_{AS} - ε_{AF})	ε_{Heat}	%
Lower cycle temperature strain	ε_{LCT}	%
Upper cycle temperature strain	ε_{UCT}	%
Residual martensite strain	ε_{MRes}	%
Residual austenite strain	ε_{ARes}	%
Work [(ε_{AS} - ε_{AF}) * σ_{App} * 100]	n/a	J/cm³
Actuation strain (ε_{LCT} - ε_{UCT})	ε_{Act}	%



Isobaric response



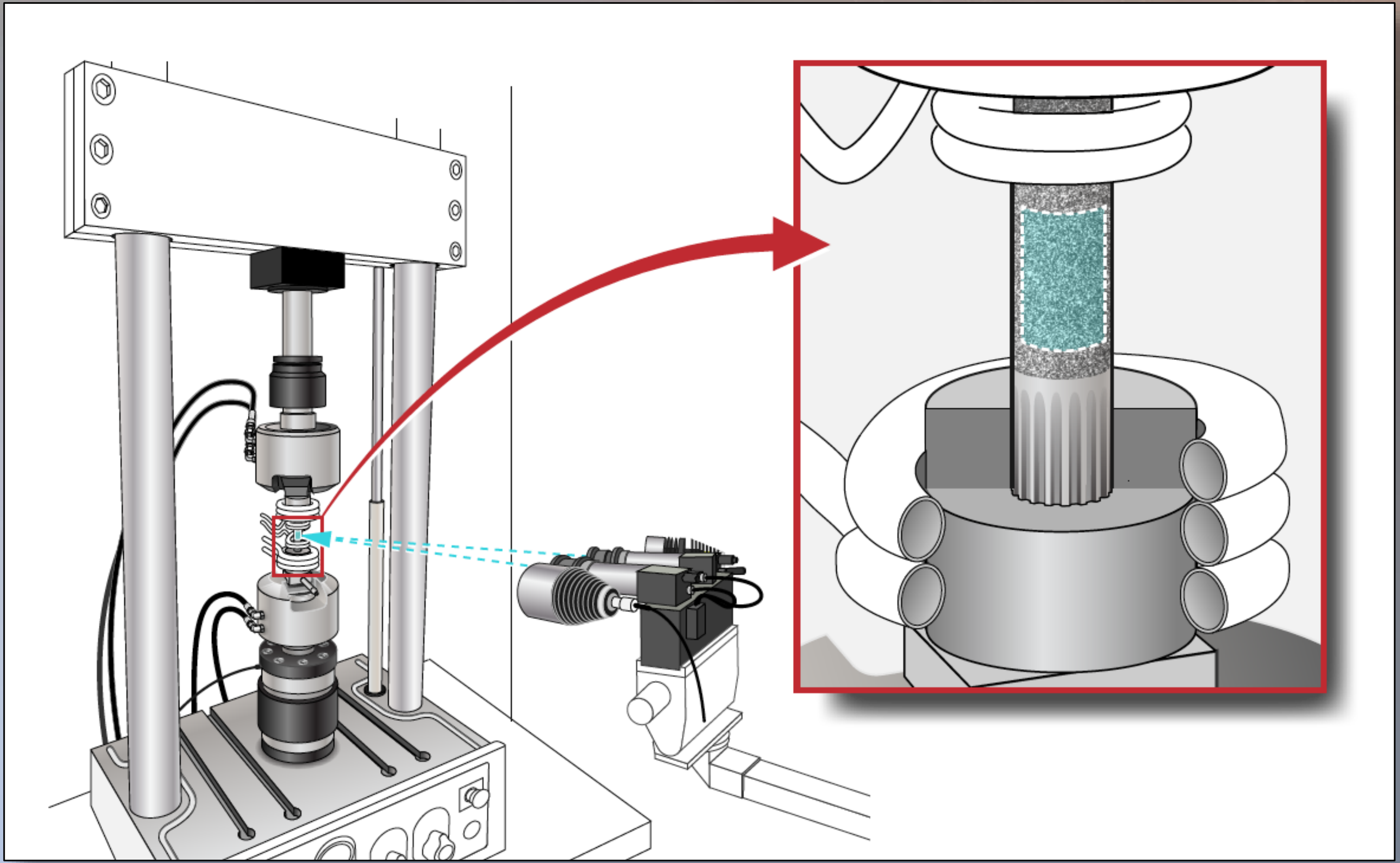
Isothermal response
+
recovery

1. *austenite finish temperature (Af)*—The temperature at which the martensite to austenite transformation is completed on heating in a single-stage transformation or the temperature at which the R-phase to austenite transformation is completed on heating in a two-stage transformation
2. *austenite start temperature (As)*—The temperature at which the martensite to austenite transformation begins on heating in a single-stage transformation or the temperature at which the R-phase to austenite transformation begins on heating in a two-stage transformation.
3. *martensite start temperature (Ms)*—The temperature at which the transformation from austenite to martensite begins on cooling in a single-stage transformation (Fig. 1) or the temperature at which the transformation from R-phase to martensite begins on cooling in a two-stage transformation.
4. *martensite finish temperature (Mf)*—The temperature at which the transformation from austenite to martensite is completed on cooling in a single-stage transformation or the temperature at which the transformation from R-phase to martensite is completed on cooling in a two-stage transformation.
5. transformation (Fig. 2).
6. *actuation strain* (e_{act})—The full strain recovery obtained when heating from LCT to UCT at a specified stress. It includes the thermal expansions of martensite and austenite as well as the phase transformation strain. $e_{act} = e_{LCT} - e_{UCT}$
7. *austenite 50%* (A_{50})—Temperature at which the transformation from martensite to austenite is 50% completed. $A_{50} = (A_s + A_f) / 2$.
8. *austenite finish strain* (e_{Af})—Strain at the austenite finish temperature.
9. *austenite start strain* (e_{As})—Strain at the austenite start temperature.
10. *hysteresis width* (HWIDTH)—Width of the thermal hysteresis curve in degrees centigrade. Distance on the temperature axis between a vertical line drawn through the A_{50} point and a vertical line drawn through the M_{50} point.
11. *initial strain* (e_0)—Specimen strain at UCT after normalizing and prior to loading the specimen.
12. *lower cycle temperature (LCT)*—Minimum temperature of the thermal cycle. It is selected to be 10 to 30 °C lower than M_f determined by a DSC test per ASTM F2004. However, the DSC test shall be done on the sample material in the same condition as the UCFTC test material.

Refer to ASTM E3097-17 and E3098-17

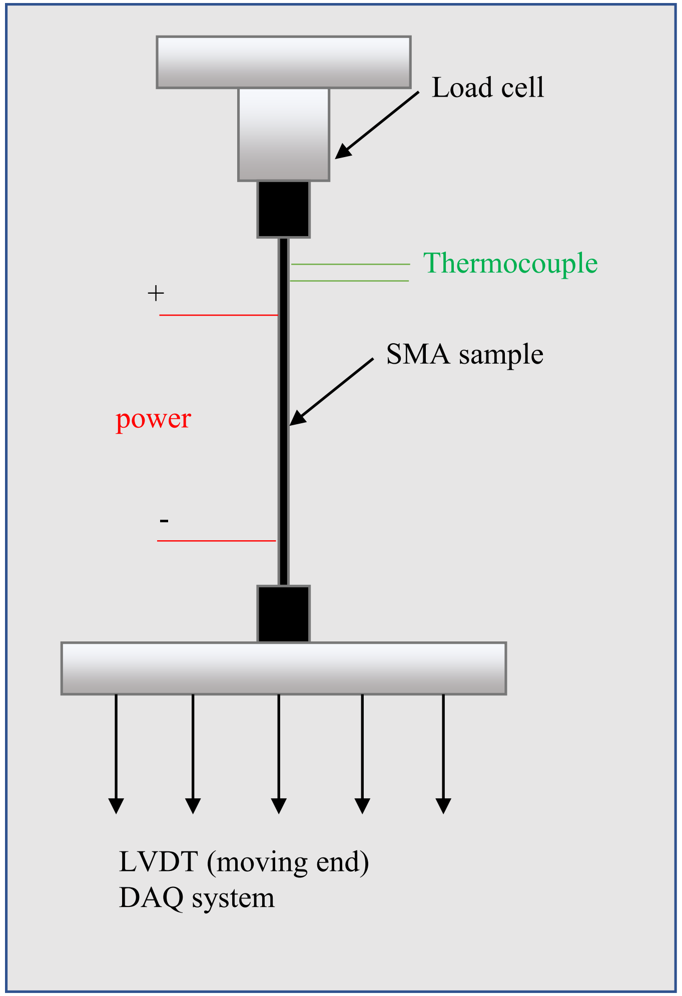
13. *martensite 50%* (M_{50})—Temperature at which the transformation from austenite to martensite is 50% completed. $M_{50} = (M_s + M_f) / 2$.
14. *initial loading strain* (e_i)—Initial specimen strain after normalization and before cooling when loaded at the UCT.
15. *residual strain* (e_{res})—The final strain at the upper cycle temperature minus the initial strain at the upper cycle temperature. $e_{res} = e_{UCT} - e_i$
16. *strain at the lower cycle temperature* (e_{LCT})—Specimen strain at the LCT after cooling from the UCT to the LCT under the specified stress.
17. *strain at the upper cycle temperature* (e_{UCT})—Specimen strain at the UCT after cooling to the LCT and heating to the UCT at the specified stress.
18. *thermal transformation span* (TSPAN)—Thermal transformation span in degrees centigrade at a specified stress. Distance on the temperature axis between a vertical line drawn through the A_f point and a vertical line drawn through the M_f point. $TSPAN = A_f - M_f$.
19. *transformation strain* (e_t)—The strain recovery due to the austenitic transformation obtained when heating at a specified stress. $e_T = e_{As} - e_{Af}$
20. *upper cycle temperature* (UCT)—The maximum temperature of the thermal cycle. It is selected to be higher than the A_f determined by a DSC test per ASTM F2004. For example, a temperature between 10 to 100 °C above A_f may be selected in consideration of the stress applied to the specimen. The DSC test shall be done on the sample material in the same condition as the UCFTC test material.
21. *initial strain* (e_0)—Specimen strain at LCT after normalizing (see section 11.1) and prior to pre-straining the specimen.
22. *maximum loading strain* (e_i)—Maximum specimen strain during pre-straining at the LCT.
23. *recovery strain* (e_{rec})—Is the amount of residual strain that is recovered in the specimen after heating to the UCT and cooling to the LCT following pre-straining, it is equal to the unloaded strain (e_u) minus strain at lower cycle temperature (e_{LCT}) after cooling from the UCT.
24. *two way strain* (e_{TW})—Specimen strain at the LCT after cooling from the UCT minus the strain at the UCT. This is the strain induced in the shape memory alloy specimen when it is cooled from UCT to LCT with an applied tensile stress of 7 MPa or less. $e_{TW} = e_{LCT} - e_{UCT}$
25. *unloaded strain* (e_u)—Specimen strain at LCT after pre-straining and then unloading, but prior to heating.
26. superelasticity—Nonlinear recoverable deformation behavior at temperatures above the austenite finish temperature (Af).

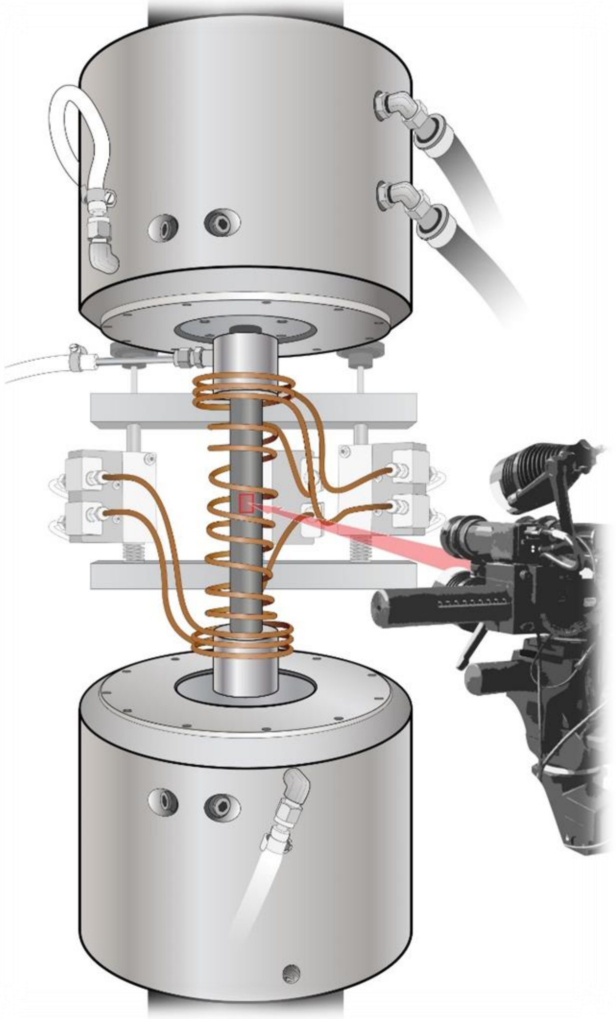
Example of thermomechanical frame



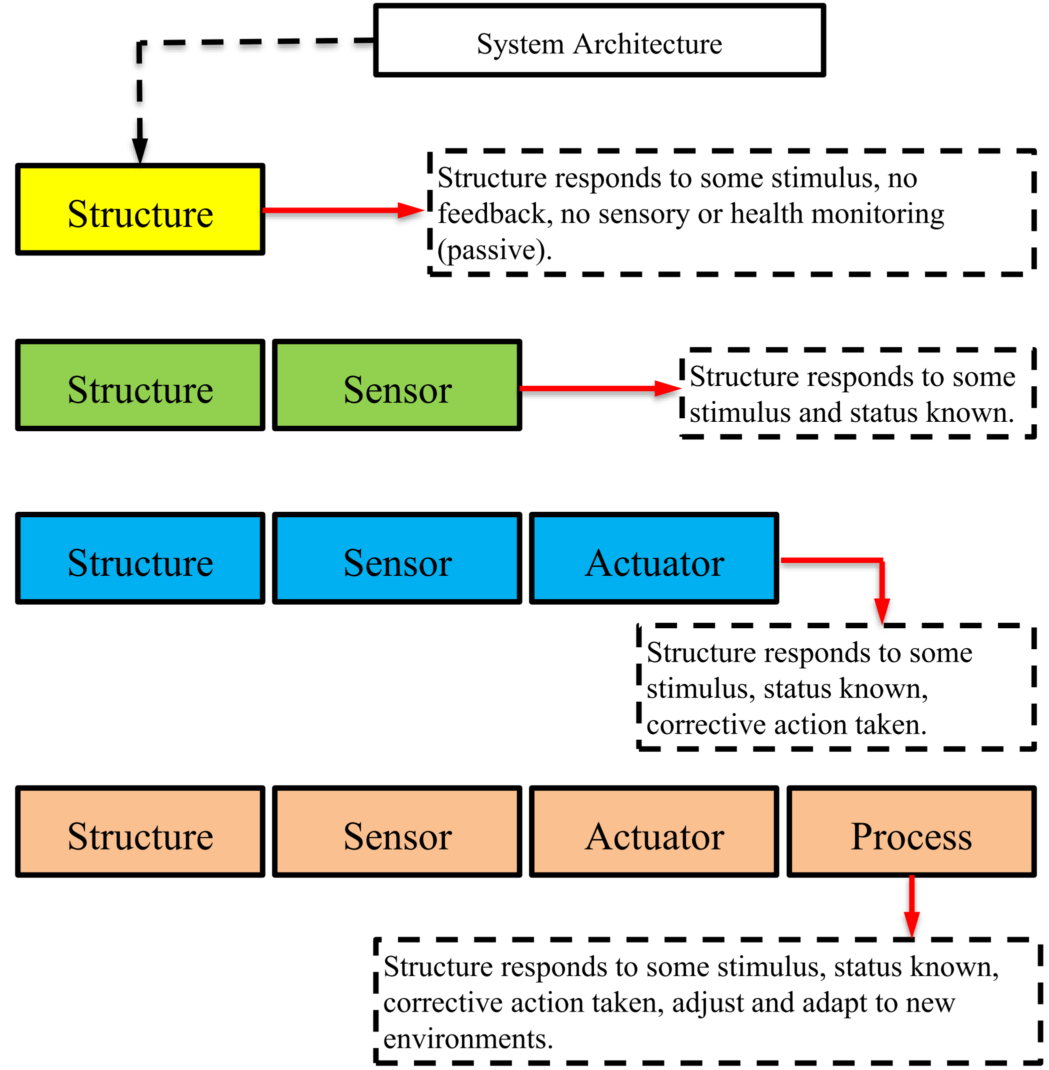
To measure properties, you need:

- Force measurements: load/torque cells, grips
- Stroke/rotation measurements: LVDT/RVDT, potentiometers…
- Temperature measurements: heaters, coolants, thermocouples…
- Strain measurements: extensometers cameras…



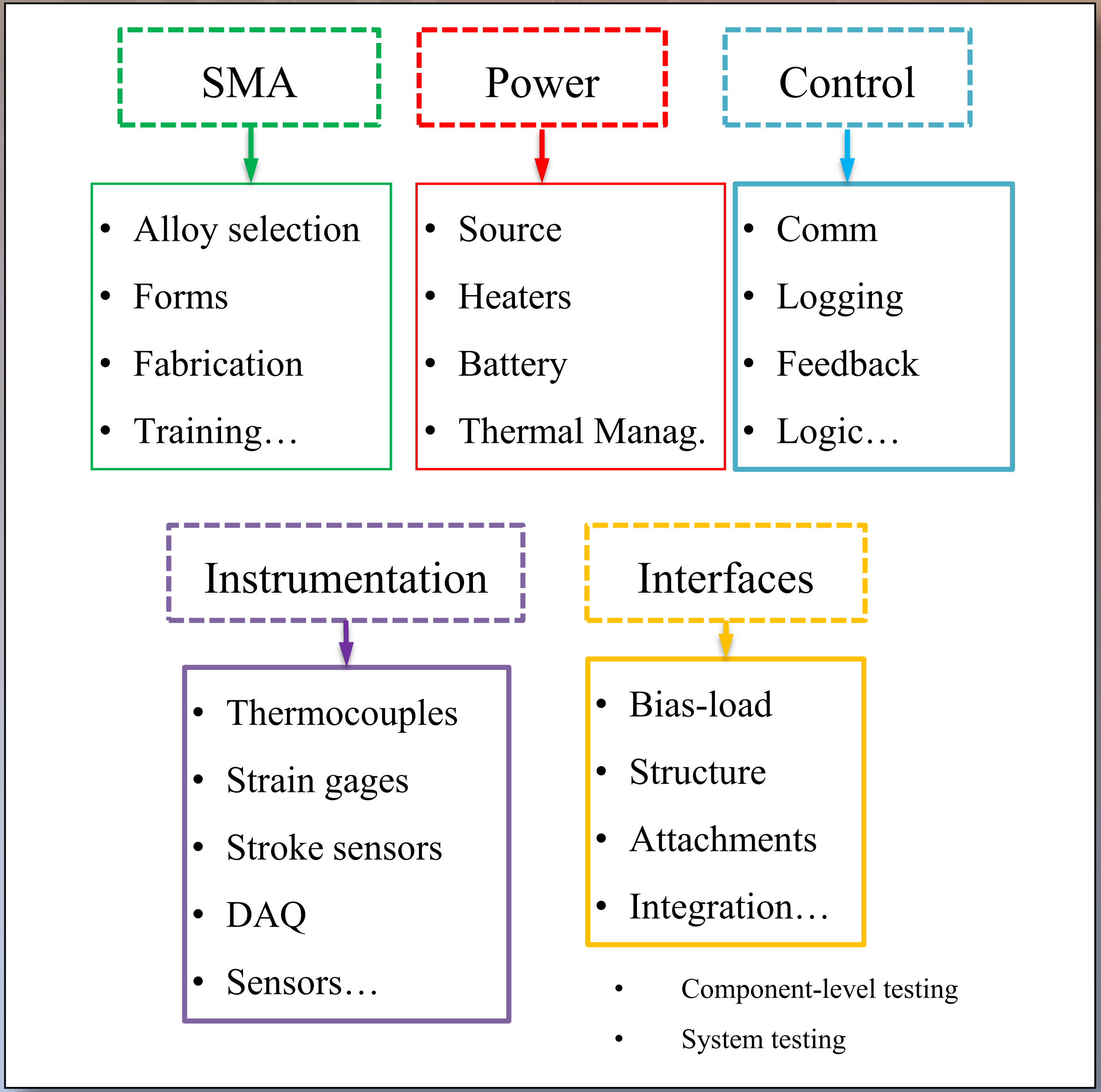


Actuation System Hierarchy—Start With the Need



For more details: A. Rao et al., Design of shape memory alloy (SMA) actuators, Springer 2015.

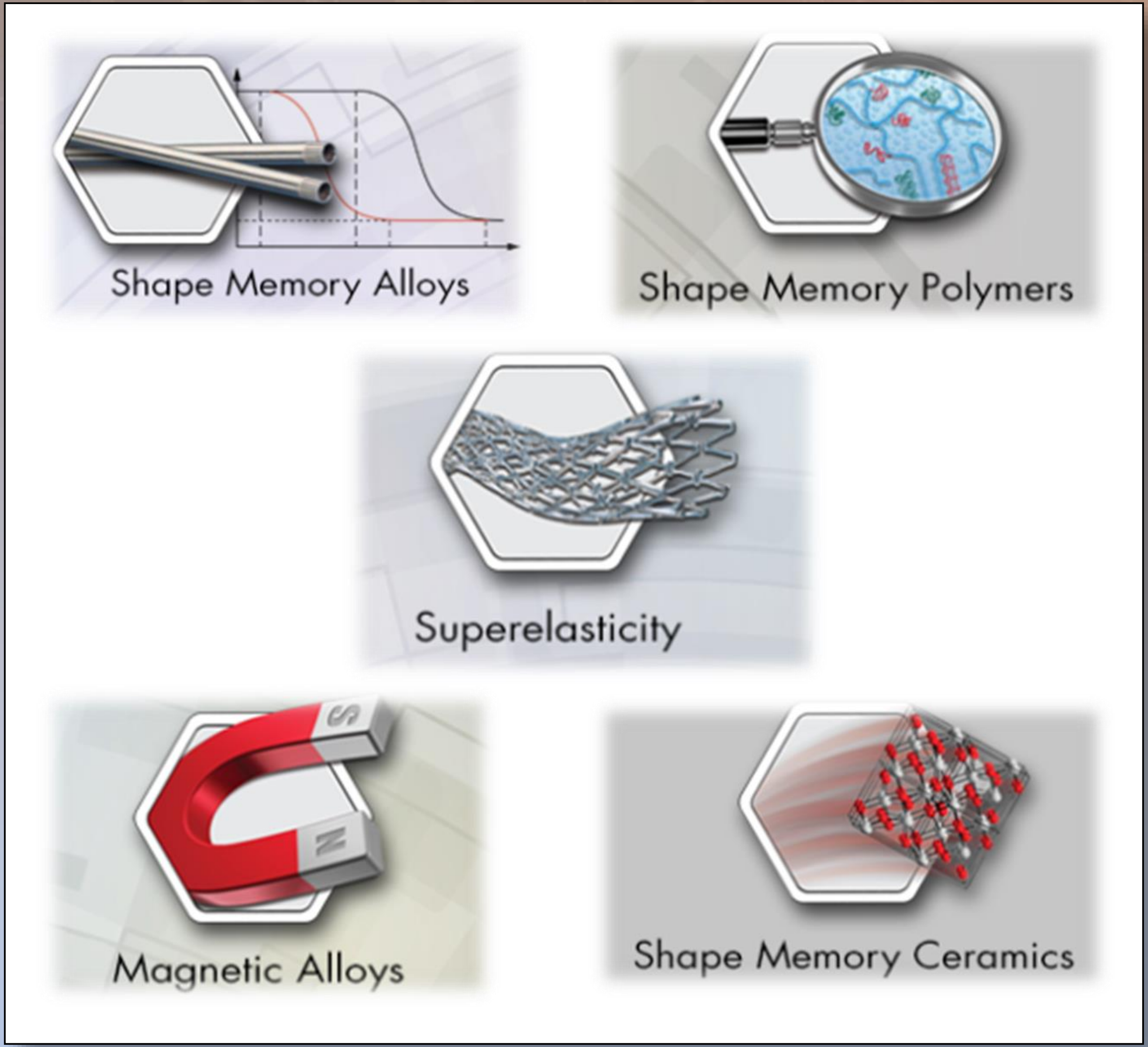
Constituent of an SMA Actuation System



SMA

Material selection

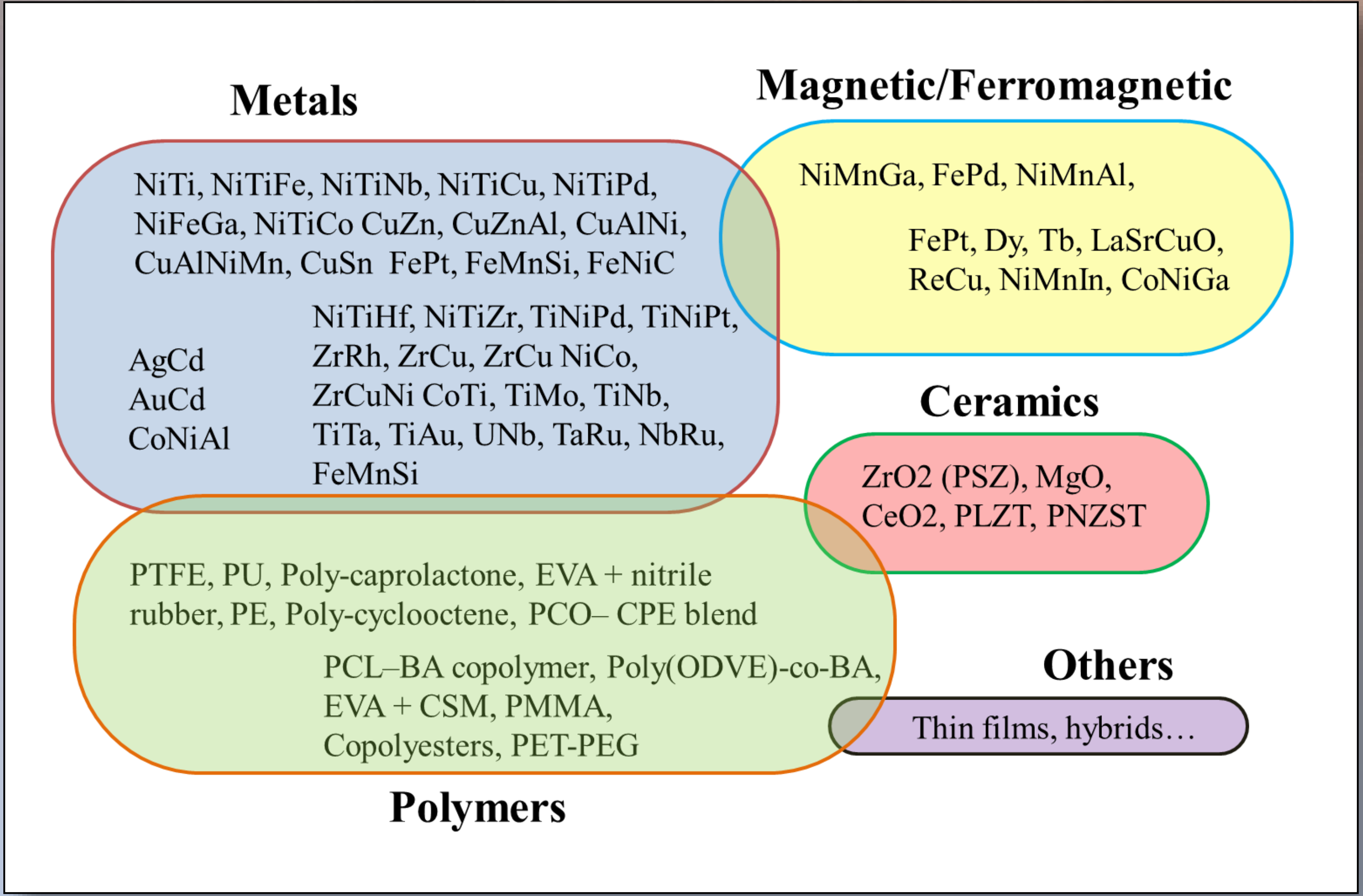
What kind of materials?



SMA

Material selection

What kind of materials?

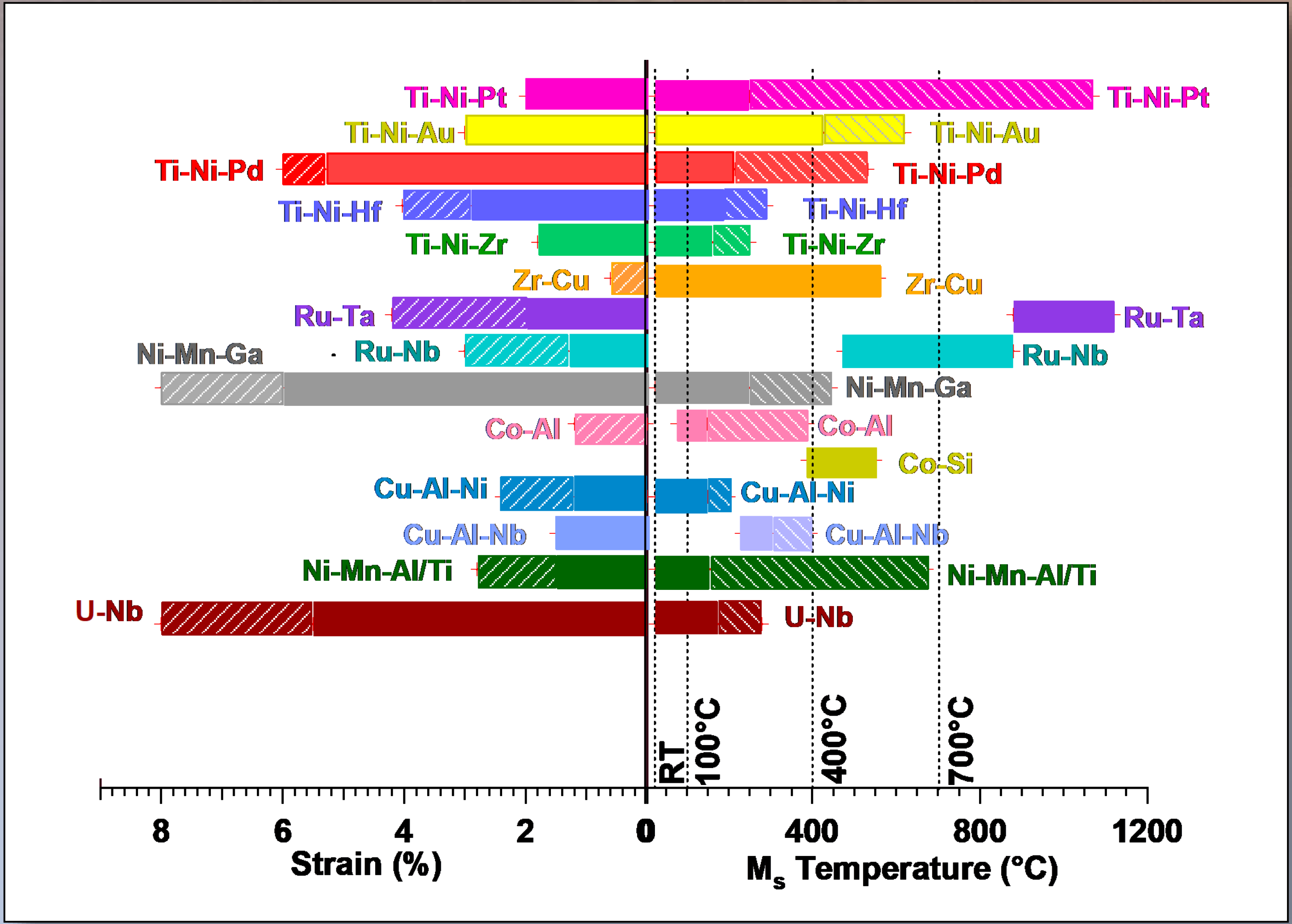


SMA

Material selection

What kind of materials?

Temperature and strain capability[23]

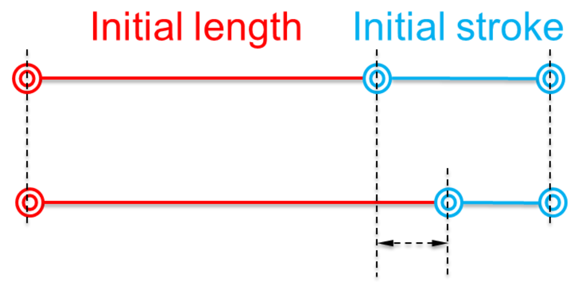


SMA

Material selection

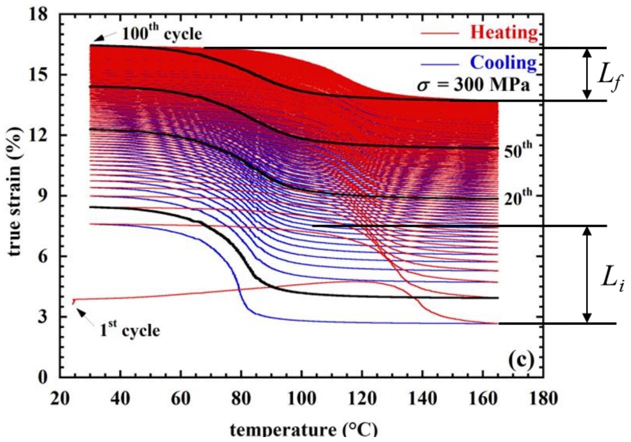
Key Parameters Relevant to Actuation

Dimensional/thermal Stability



Need training

Durability/fatigue

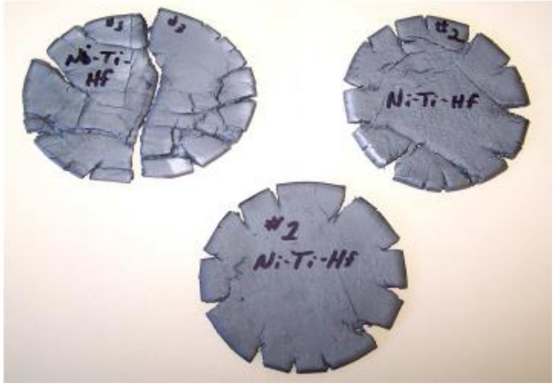


SMA

Material selection

Key Parameters Relevant to Actuation

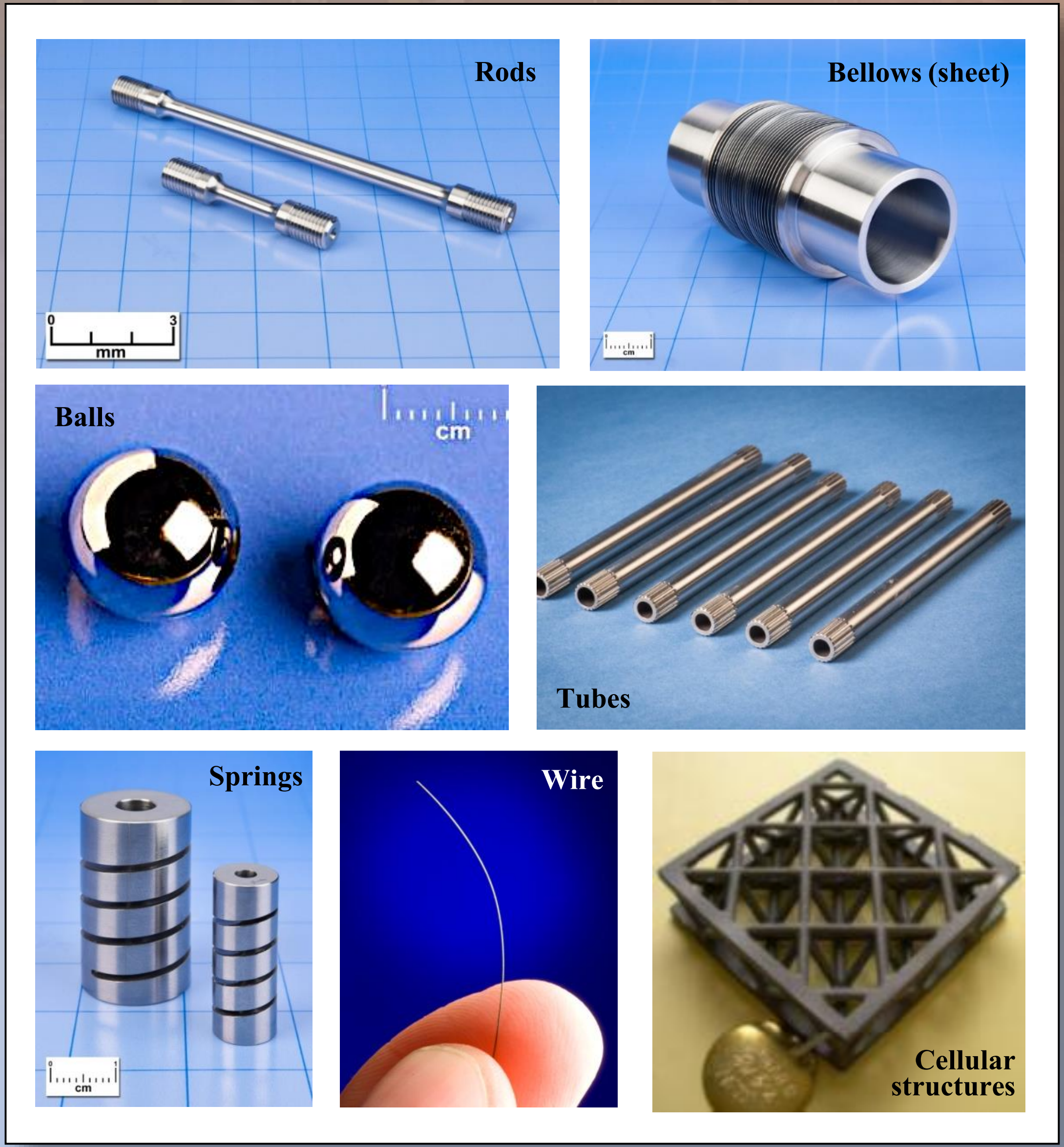
Workablility/processing



(C.Wojcik 2008)

SMA

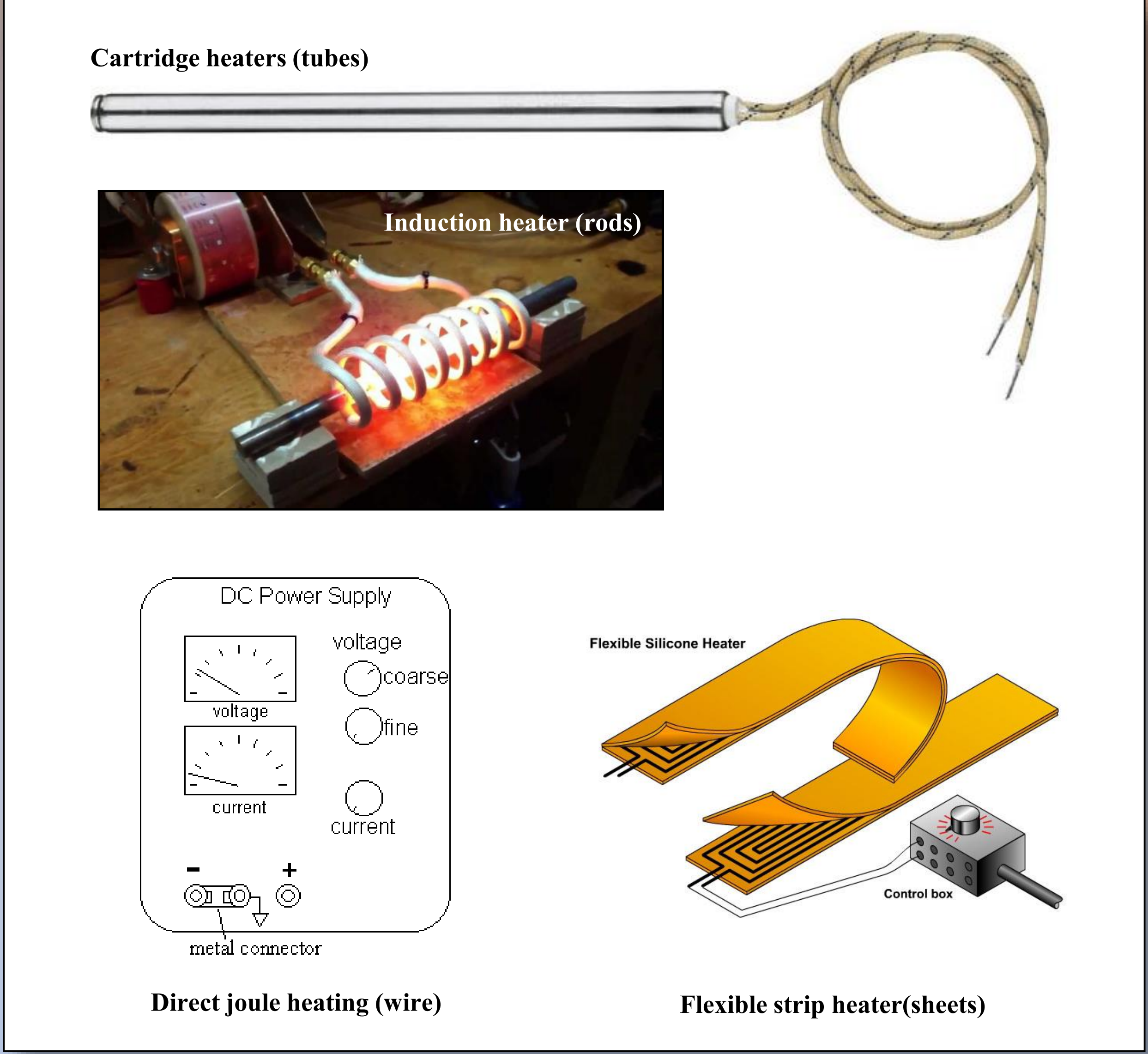
Forms


Rods
0
3
mm
Bellows (sheet)
Balls
cm
Tubes
Springs
cm
Wire
Cellular
structures

Power

↓

Sources and devices →



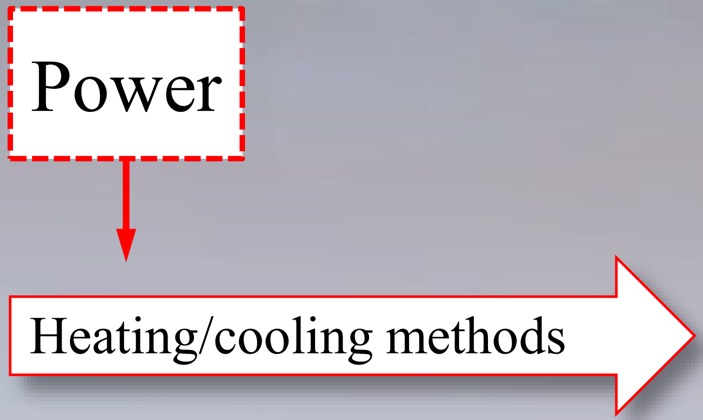
Power

Heating/cooling methods[24]

Table 1. Potential heating and cooling methods for shape memory alloys.

Heating	Cooling
Direct resistive	Free convection (air)
Capacitance-assisted resistive	Liquid immersion
Conductive	Forced air/liquid convection
Convective	Peltier effect
Radiative (including laser)	Heat sinking
Inductive	*Cool Chips* technology[a]

[a] Electron transport across a vacuum diode. Suitable for miniaturized applications such as micro-robotics.



Things to watch for:

- Thermal gradients (e.g., may reduce strain output)
- Over temperatures (e.g., may deteriorate training)
- Heating/cooling rate:
    - ✓ Trade-offs based on system
    - ✓ Joule heating for small wires may work, but won’t be feasible for big torque tubes
    - ✓ Induction heating may work for big rods, but require high power
    - ✓ Don’t forget about passive actuation (sun power, exhaust heat…)

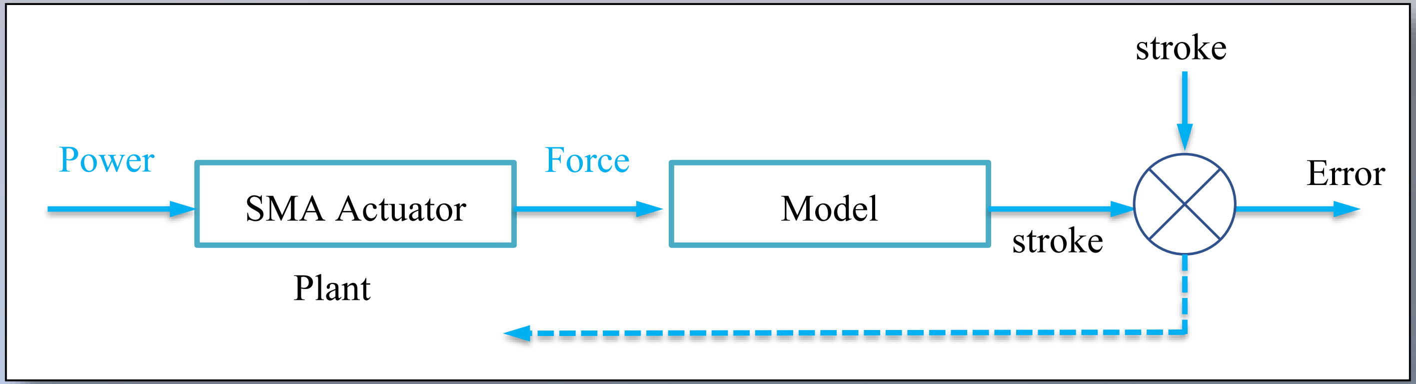
Control

Controls

Control of SMA actuation system can be challenging:

- Nonlinear nature and multiple dependencies of SMAs (stress, temperature, hysteresis…)
- Heating and cooling (overruns, overshoots, minor loops…)
- Number of unknown state variables (phase fractions…)

It is not just on-off system (2 state), feedback control is doable.



Instrumentation

Sensors
SMA sensory function (example)

What sensors, where to place them and how many?

- Thermocouples (or similar) to monitor temperatures.
  - Need to monitor the SMA elements and possible heat leak to surrounding structures
- Position sensors to monitor stroke and/or angular displacement
- Strain gauges or load cells
- Power monitoring (voltage, current)
- Wire routing and management

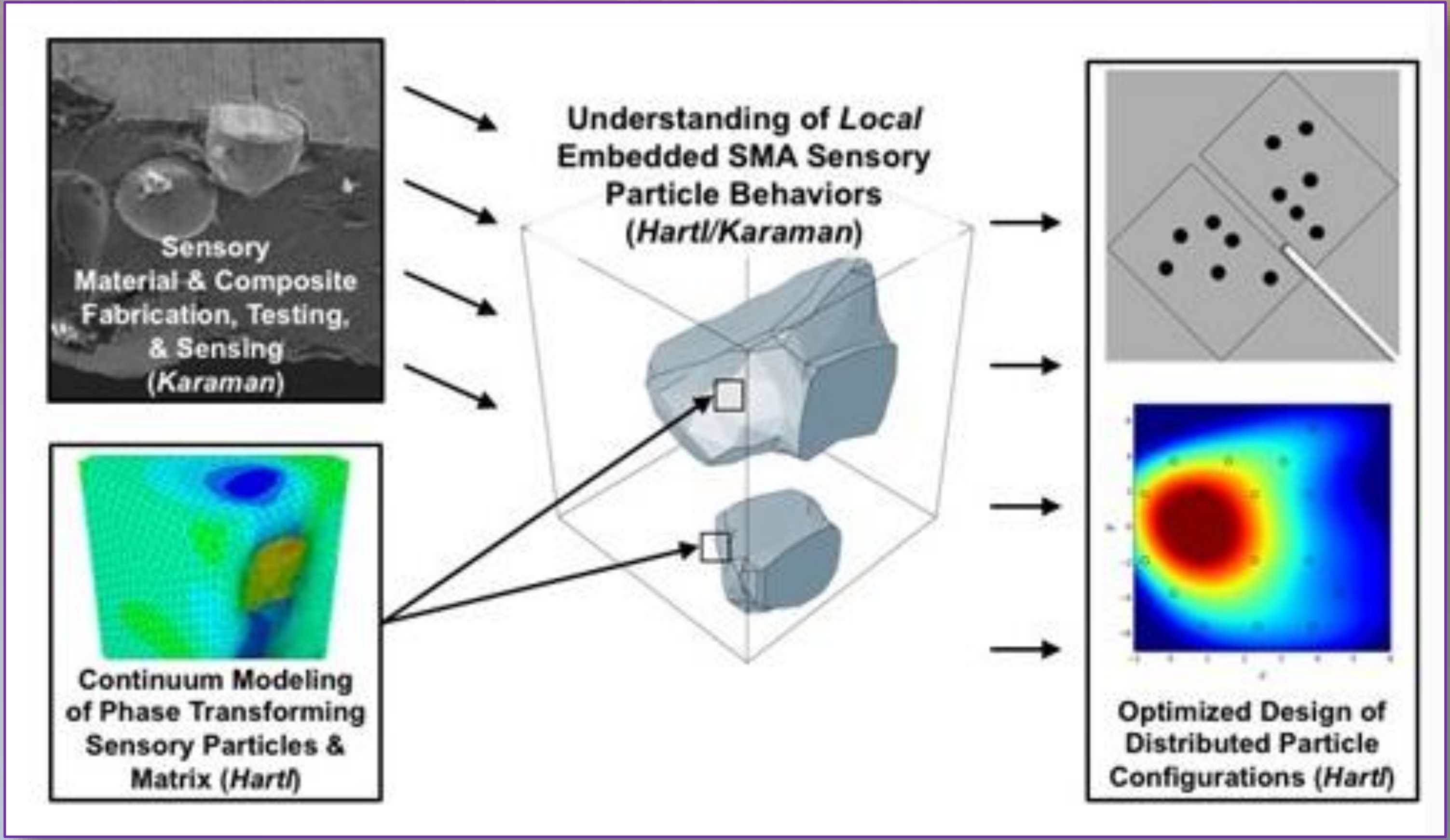
Can SMA be the "sensor"? YES

- Self-sensing (e.g., resistivity)
- Health monitoring

Instrumentation

Sensors

Contols, monitoring, safety



https://engineering.tamu.edu/news/2017/08/01/embedded-shape-memory-alloy-sensory-particles-may-detect-damage-in-aircraft-and-spacecraft.html

Interfaces →

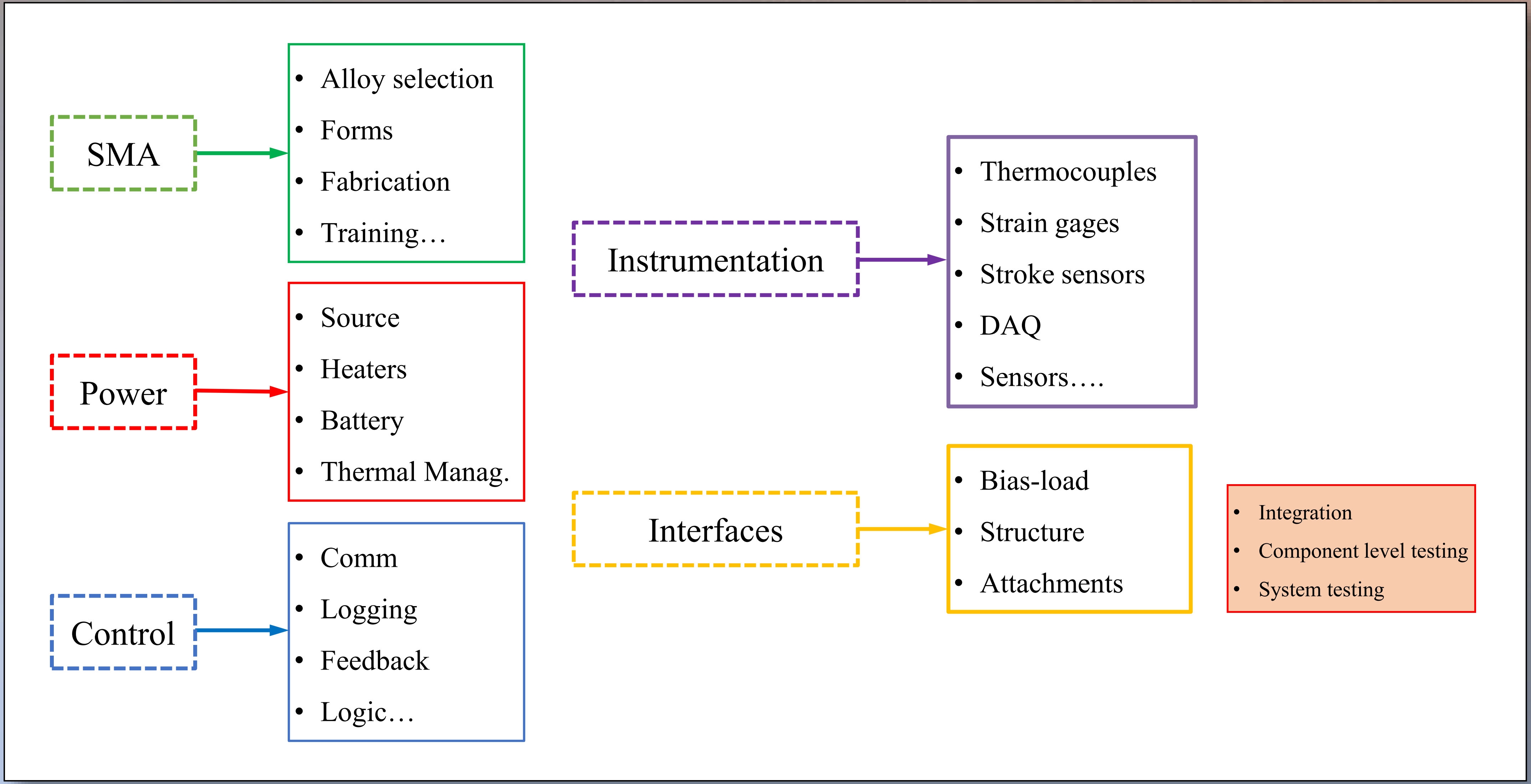
Mainly:

- How to transfer the SMA-load to the structure
- The bias-load:
  - Can be an external element (e.g., springs)
  - Can be part of the structure (e.g. weight)
  - Can be part of the environments (e.g., aero loads)
  - Can be part of the SMA itself (two-way shape memory effect)
- Attachment, joining, welding

Mechanisms:

- Material → motor→ actuation system
  - Bearing structures
  - Locking features
  - Mounts…

Constituent of an SMA Actuation System



References

22) A. Rao et al., Design of shape memory alloy (SMA) actuators, Springer 2015.
23) J. Ma et al., High temperature shape memory alloys, International Materials Reviews, Vol. 55 (2010)
24) Saunders et al., Smart Mater. Struct. 25 (2016) 045022 (20pp)
25) ASTM E3097-17, Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys, ASTM International, West Conshohocken, PA, 2017, www.astm.org
26) ASTM E3098-17, Standard Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys, ASTM International, West Conshohocken, PA, 2017, www.astm.org

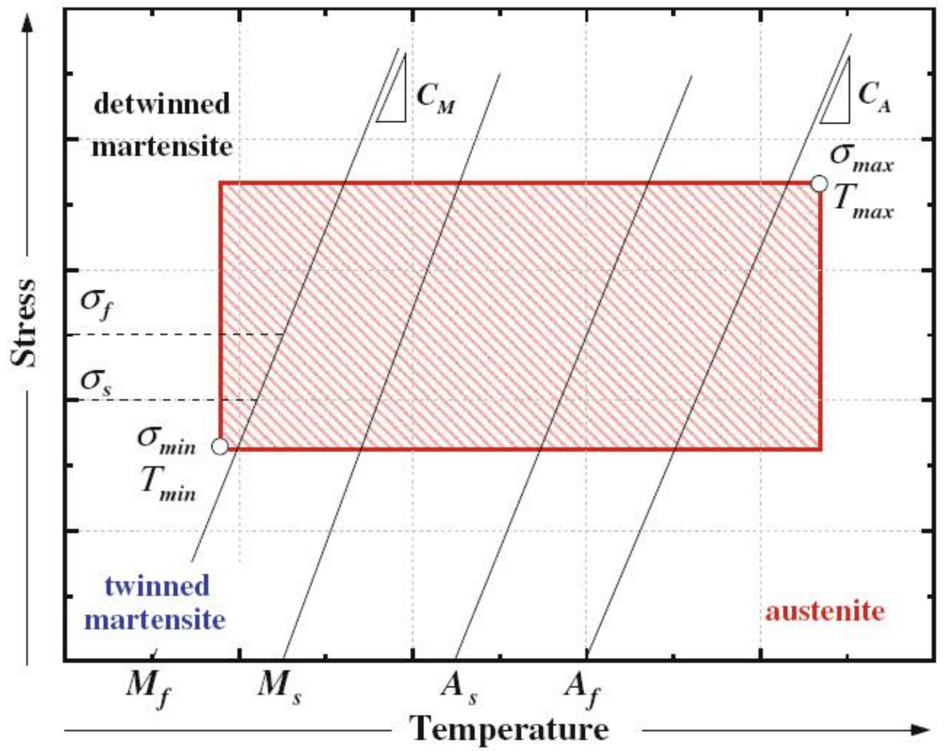
Linear and Rotational Motions—Build your first SMA model

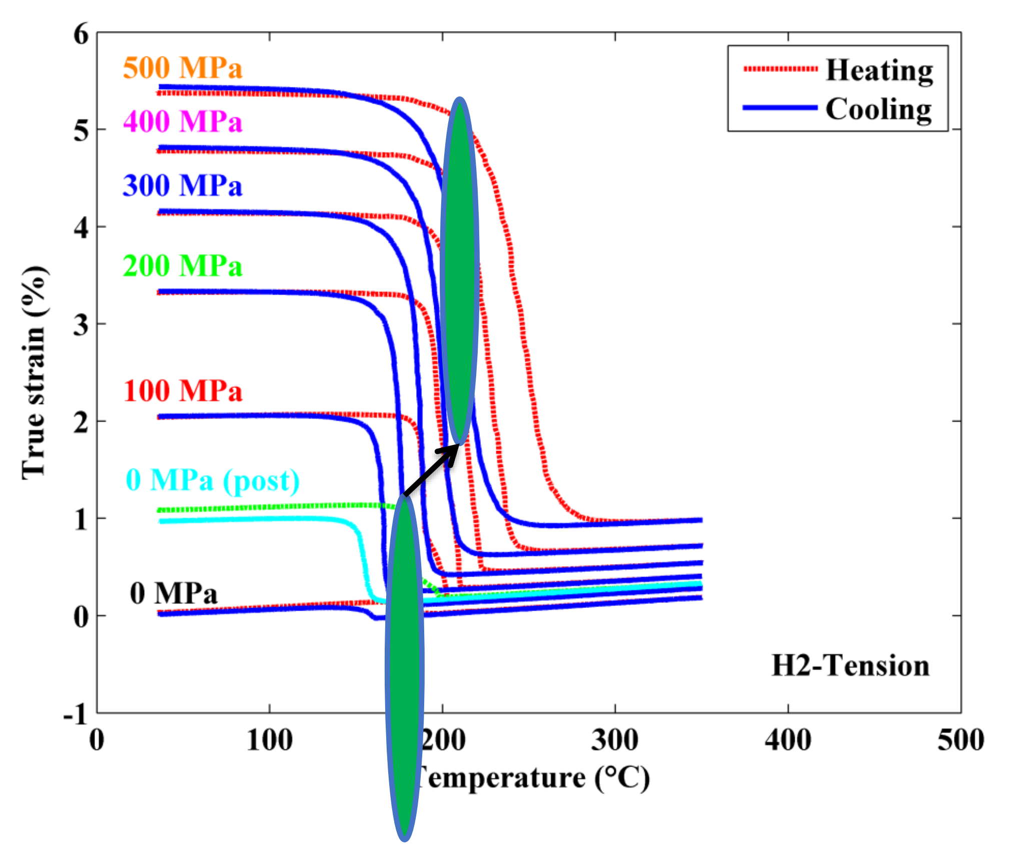
(Group exercise)

1. From the provided kit
    - Identify type of SMA element
    - Identify type of mechanism
    - Identify input parameters (power…)
    - Identify output motion/force

2. Build your kit.

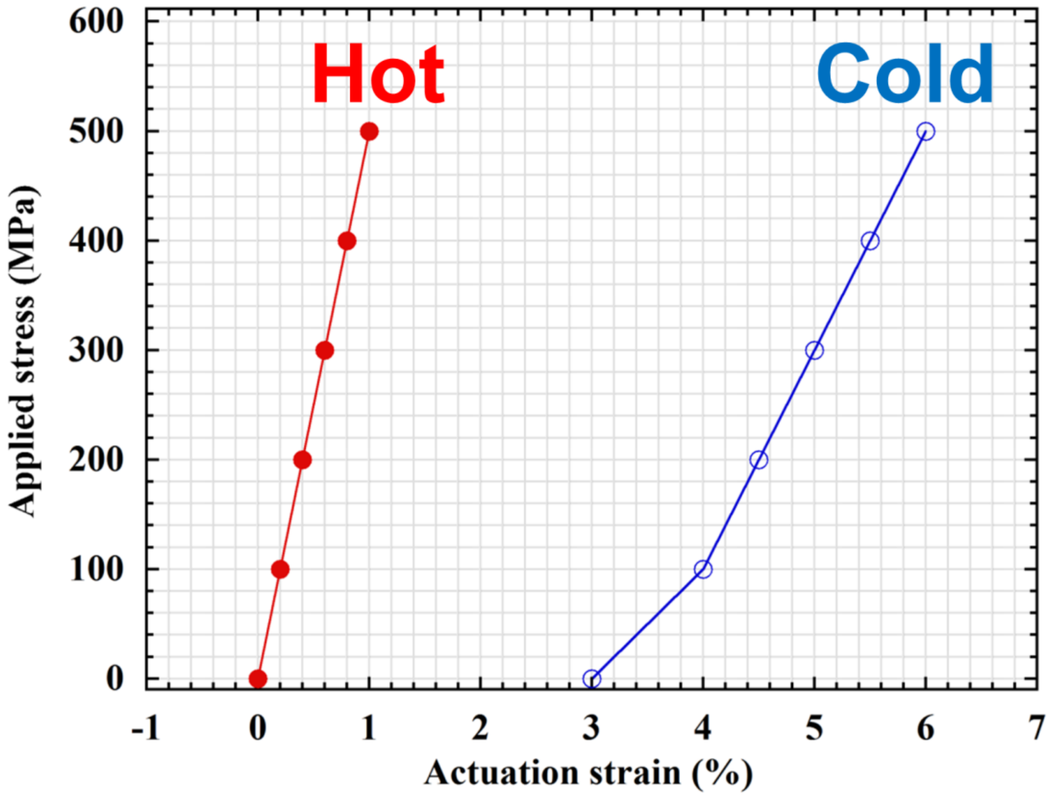
Stress-temperature relationship

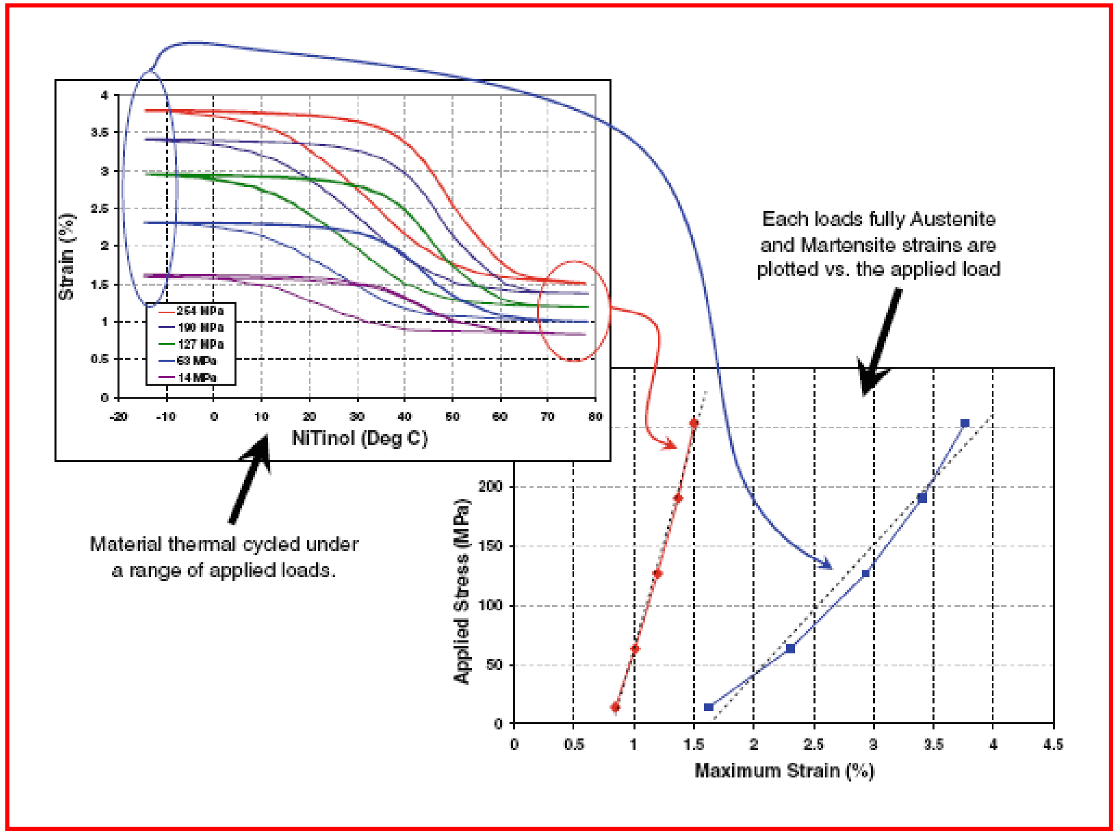




This is how you obtain it

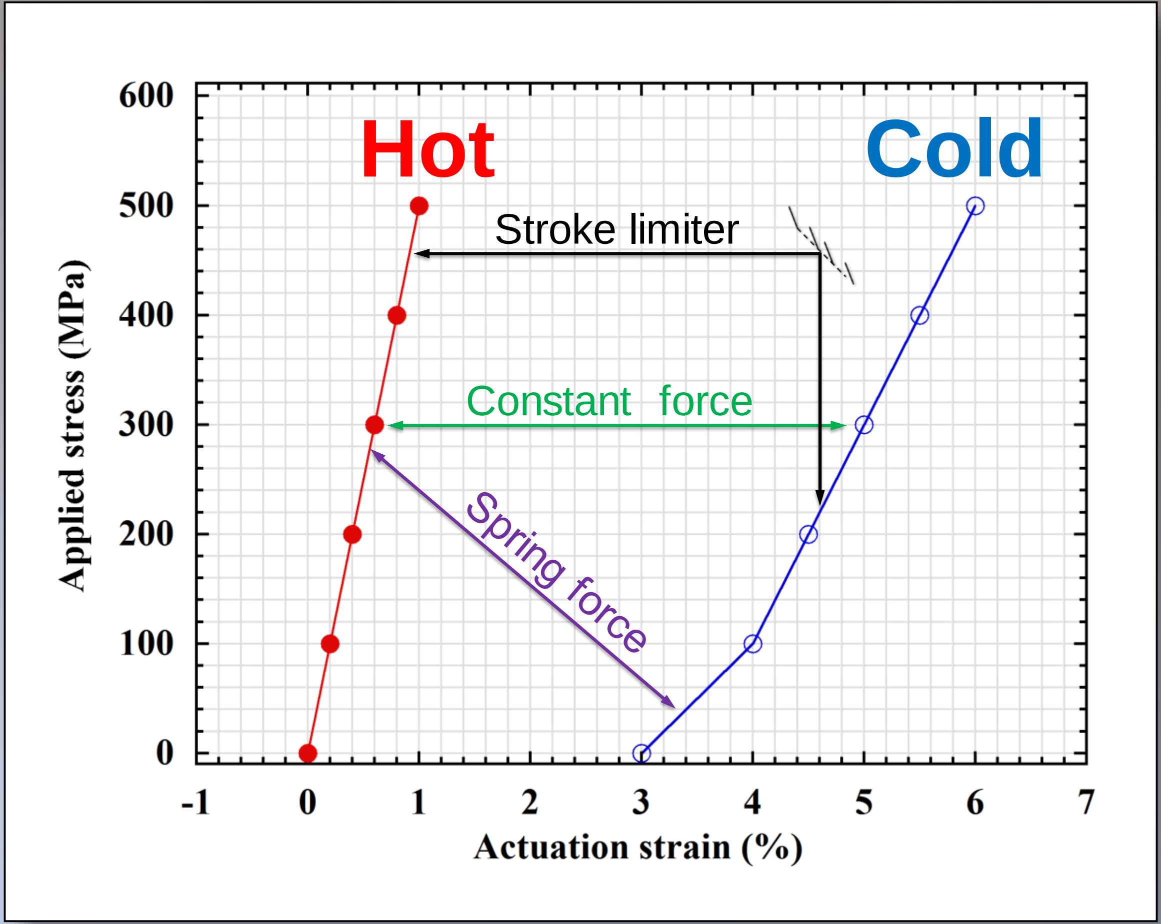
Stress-temperature relationship





This is how you obtain it

Understanding load-lines



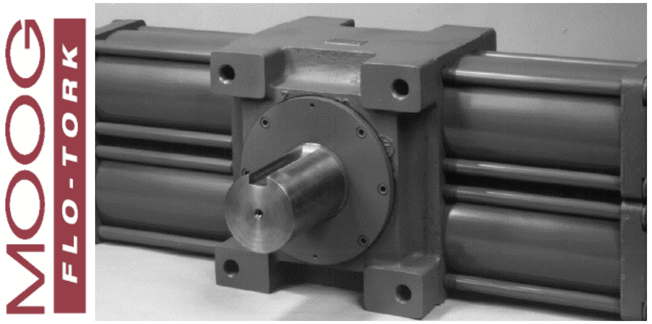
- Stroke limiter (example: mechanical stop…)
- Constant force (example: dead weight…)
- Spring force (example: variable loading, change in CG, pressure drops…)

Case study

Comparison of a "Simplified" Actuation System (Weight and Size)

*Assume the need for 100,000 in-lbf actuator

HYDRAULIC ACTUATORS



PNEUMATIC ACTUATORS

	Model #150000	Model #HTR150
Rotation (°)	90	90
Footprint (in)	25" x 9" x 12", 2700 in^3	27" x 11.5" x 13", 4036 in^3
Output Torque (in-lbs)	100,000 in-lbs @ 2000psi	100,000 in-lb @ 2000psi
Operating temperature (F)	0 to 200 F	-40 to 250 F
Weight (lbs)	**330 lbs**	**321 lbs**

Case study

Comparison of a "Simplified" Actuation System (Weight and Size)

*Assume the need for 100,000 in-lbf actuator

SMA Actuator**

Model # AMS2018

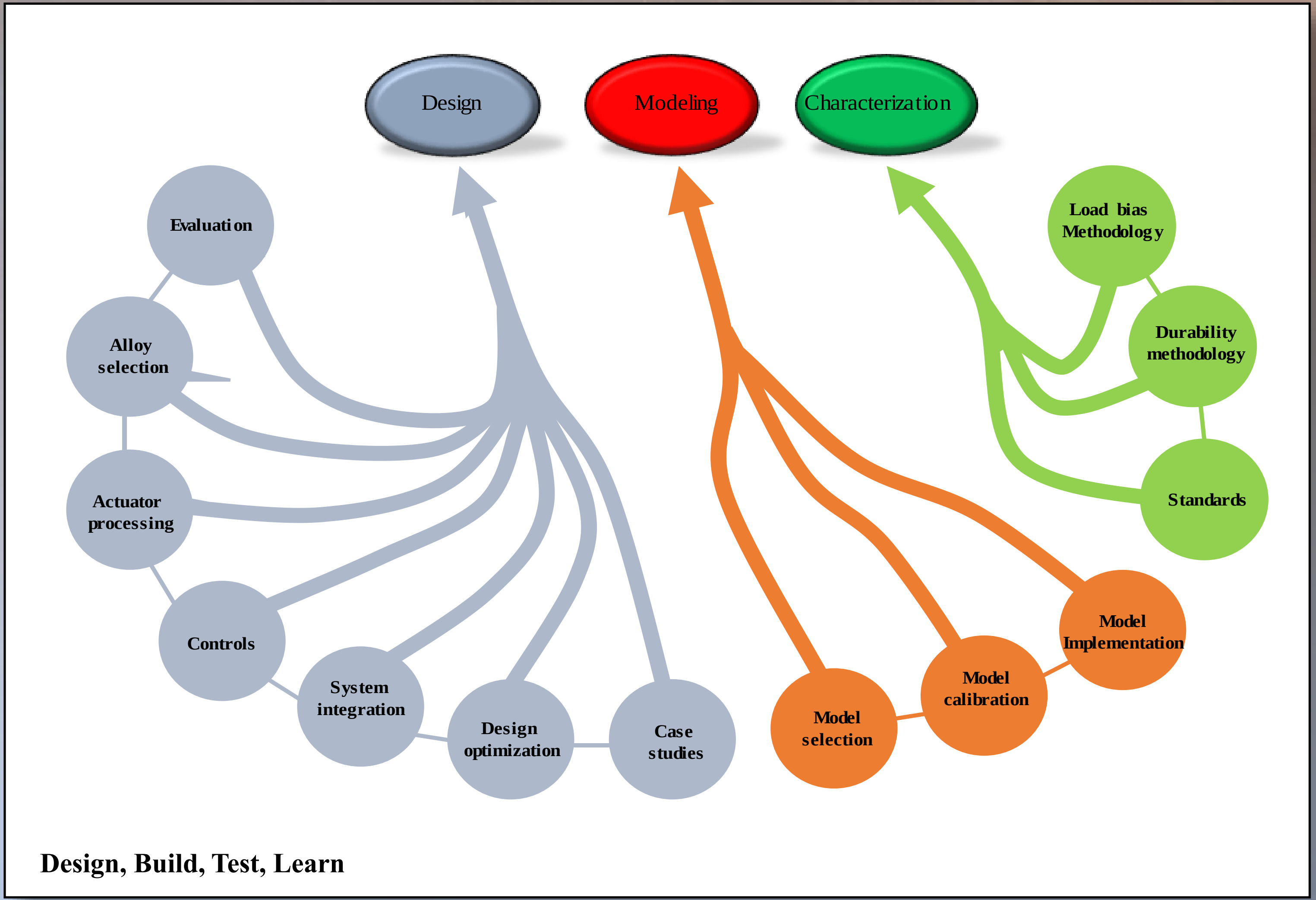
- Size ~450 in^3
- Weight ~58.5 lbs
- Temperatures~ tunable based on alloy used
- Torque ~ 100,000 in-lbs
- Angle ~ 90 deg
- **20% the weight and 15% the size of comparable hydraulic system**

**Modeled after: NiTi, 3% strain, 1" OD torque tubes

Does SMA make sense for my application?[27]

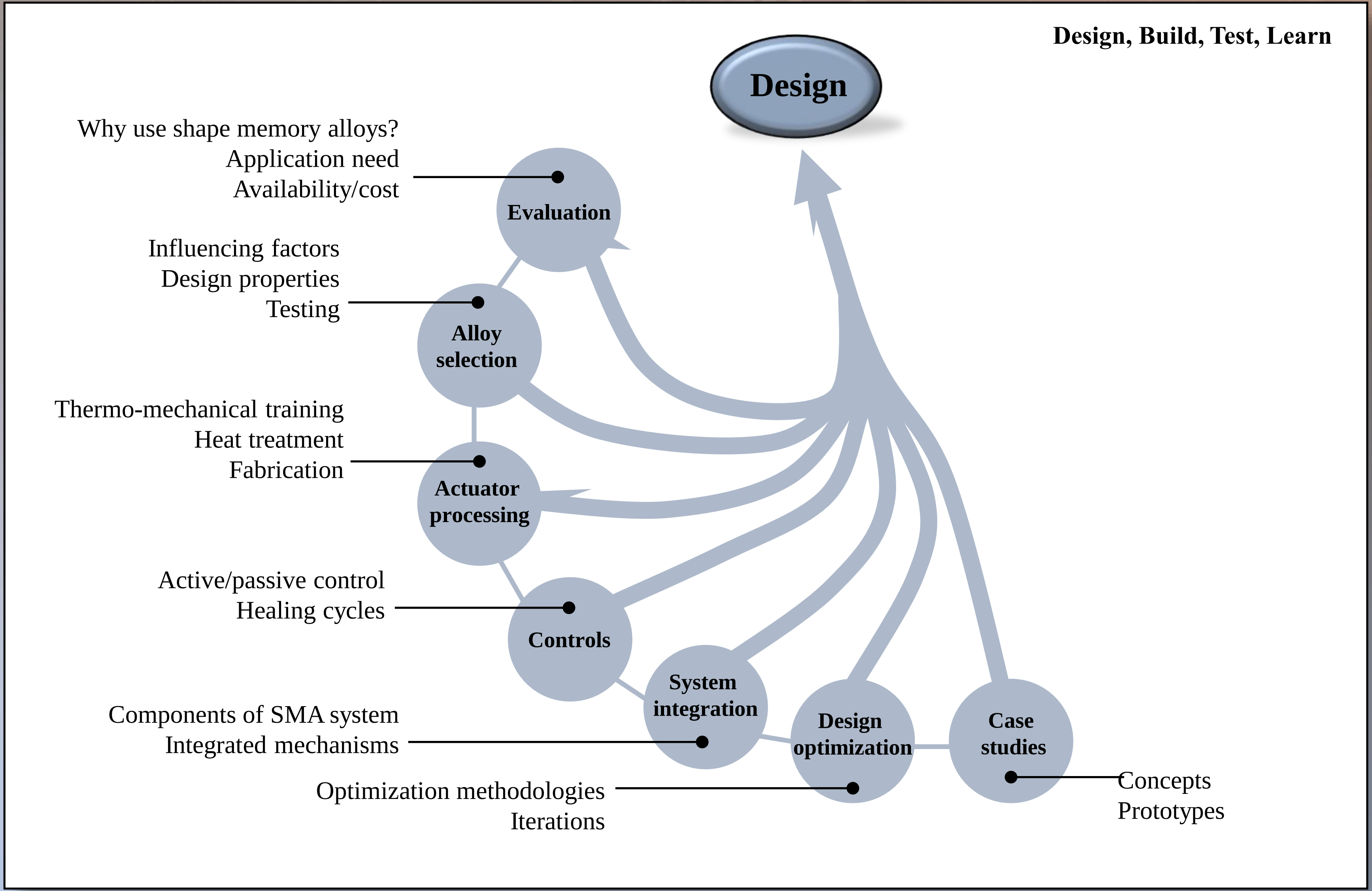
- *Why use shape memory alloys?*
  - Identify potential advantages over other systems
- *What are the application requirements?*
  - Required properties and performance characteristics of SMA element
  - Lifecycle, response time, conditions
  - Choice of material, form, size, and control methods
- *What are the cost/expenditure limits?*
  - Raw SMA material, processing, and fabrication
  - Cost per device is critical to the business case
- *What is the availability and size of the SMA element?*
  - Input (power) and required output (work) of the SMA element
  - Forms (e.g., strips, rods, sheets, wires, springs, tubes, etc…) in various sizes
  - Availability and required volume of the material from a commercial supplier or other source
- *What efficiency and response time is needed?*
  - Energy and mechanical efficiencies of SMA components
  - Weight savings (mass efficiency) may be of higher priority
  - Cyclic frequency
- *What is the proposed environment?*
  - Environment and thermal conditions
  - Commercial availability of alloys, transformation temperatures are limited to ~115 °C
  - Vibration, humidity, corrosive elements, and bio-compatibility
- *What relevant standards and documents are available?*
  - Required for certification
  - Examples include ASTM standards: application specific documents, certification documentation, and supplier data
- *What other components/system will be required?*
  - System components

Design cycle [27]



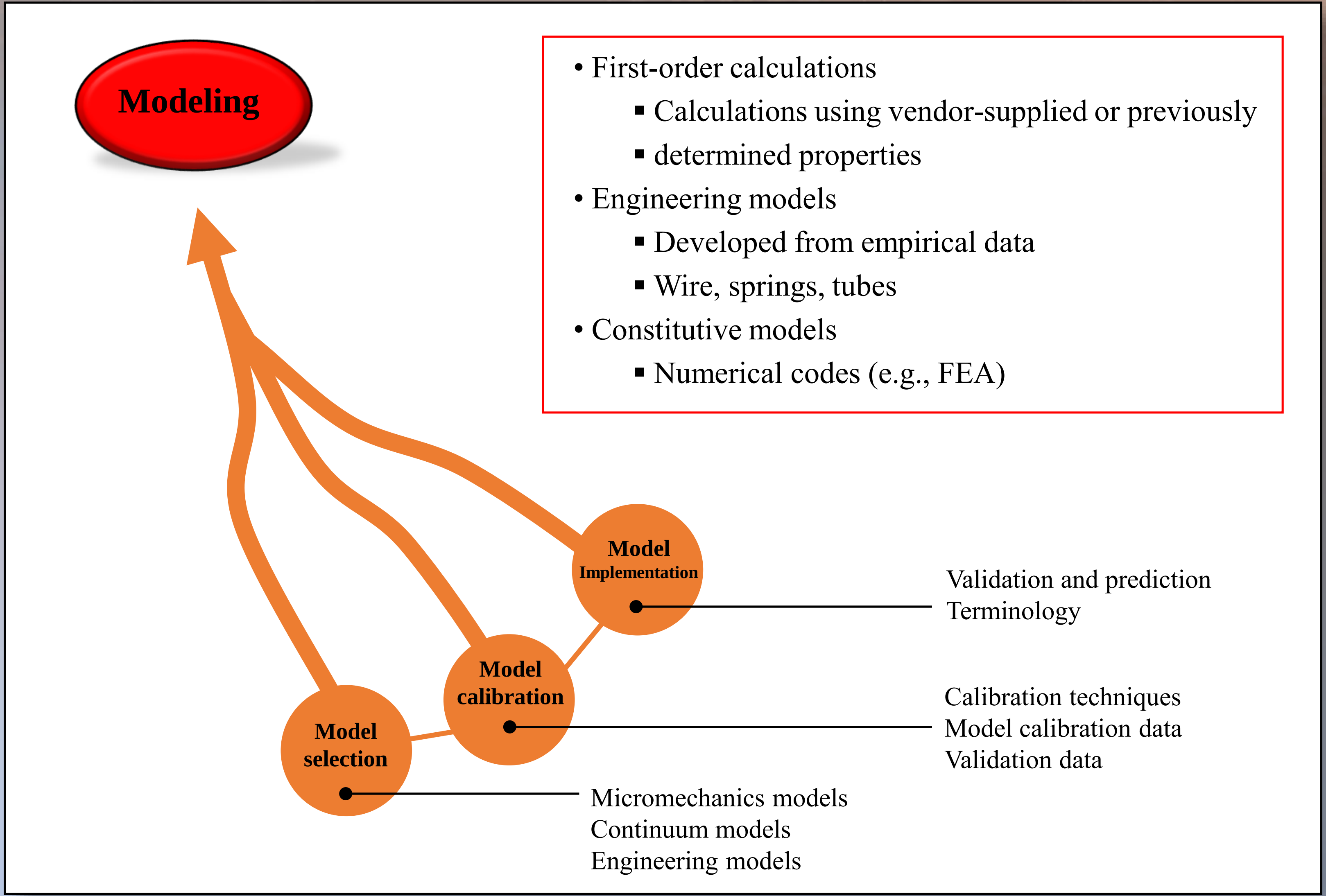
Courtesy: CASMART

Design cycle [27]



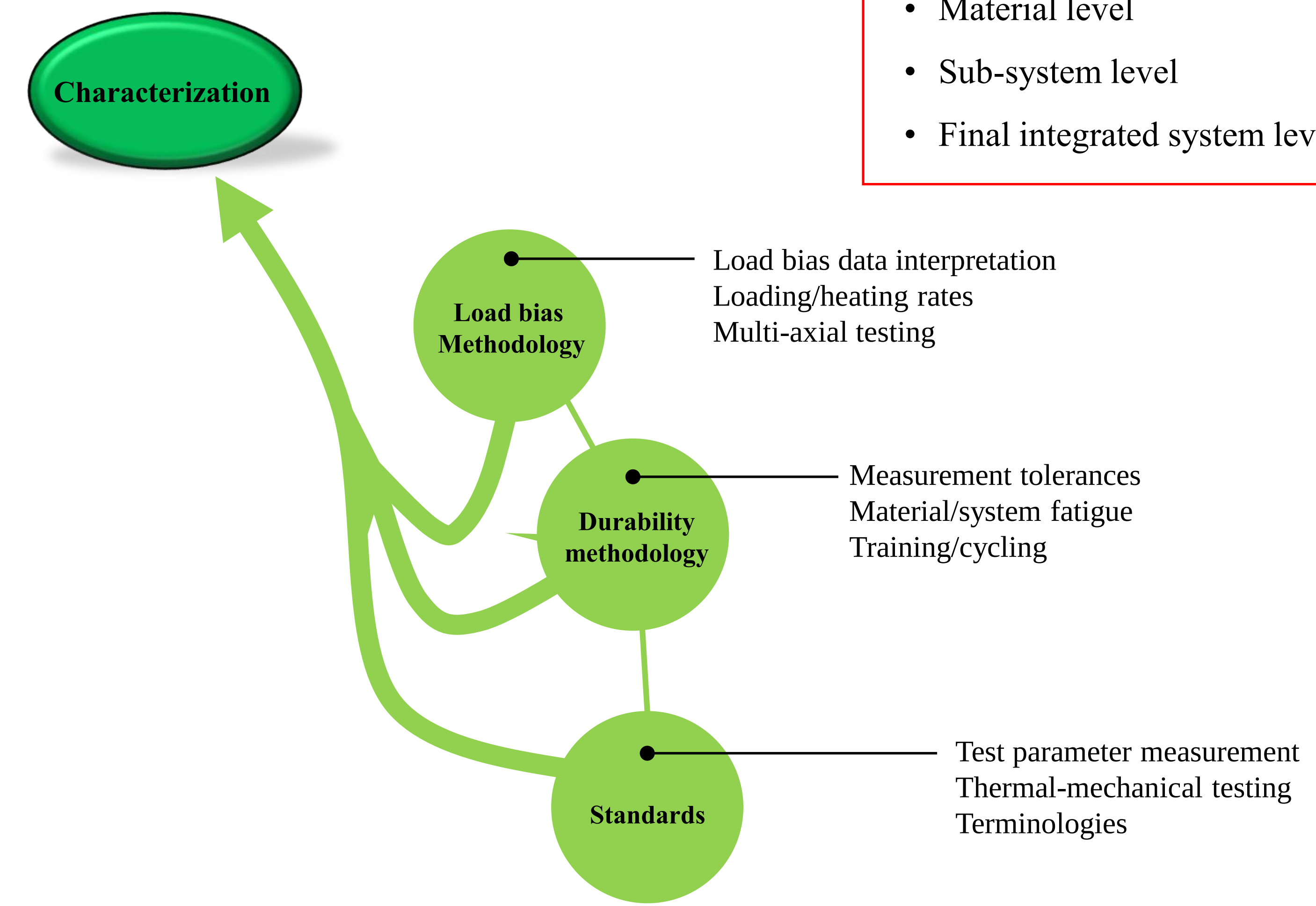
Courtesy: CASMART

Design cycle [27]



Courtesy: CASMART

Design cycle [27]



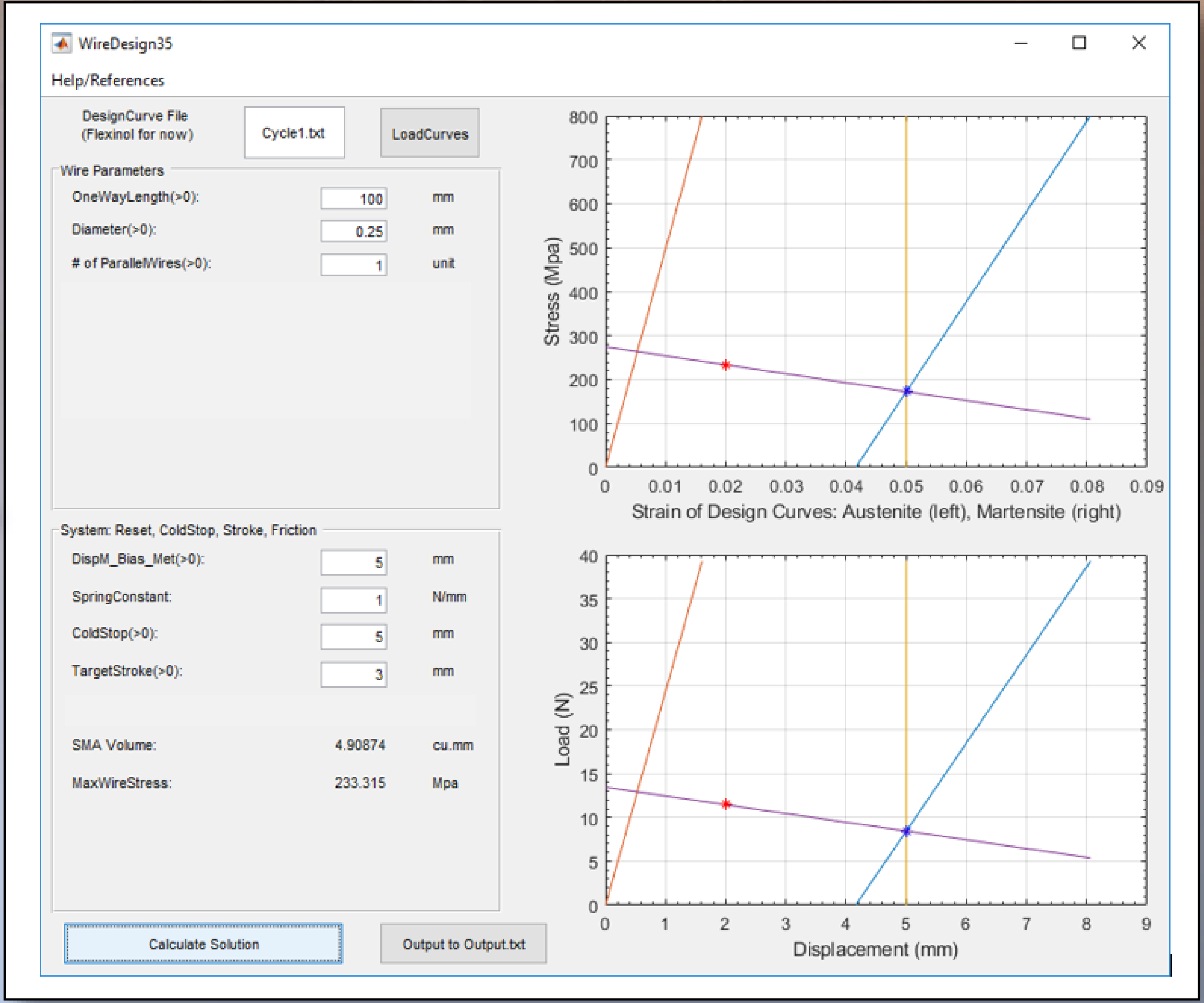
- Material level
- Sub-system level
- Final integrated system level

Courtesy: CASMART

Wire Design Tool[28]

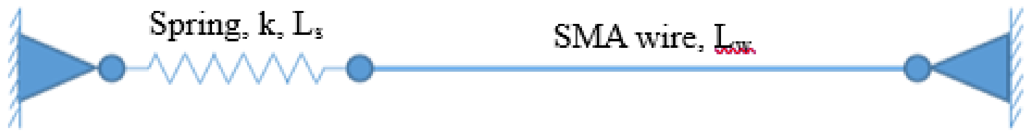
- User-input martensite and austenite stress-strain responses

Solve for strokes, loads, and predicted life



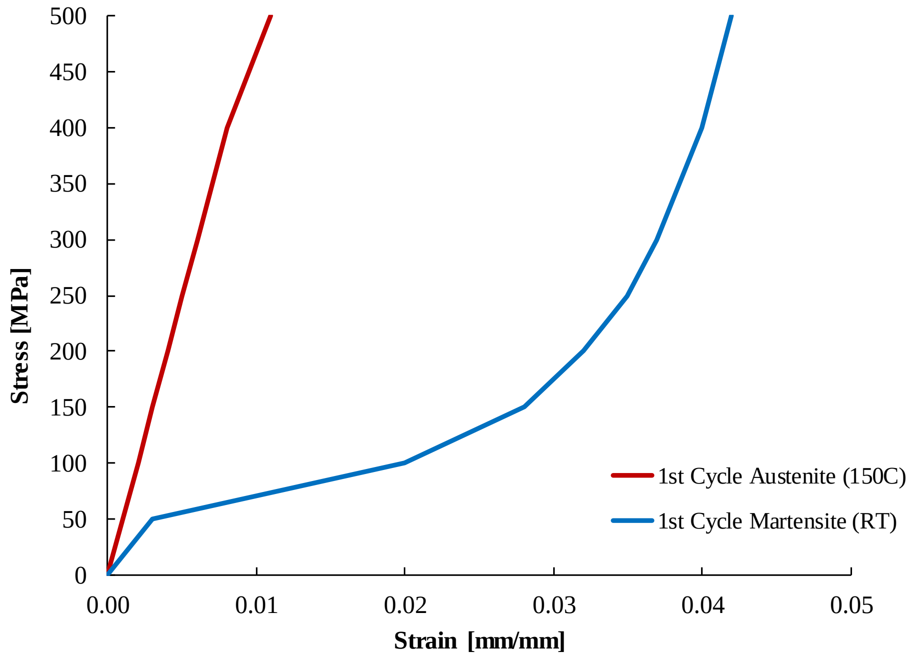
Wire Design Tool[28]

- Wire is rigidly anchored at one end and attached to a linear bias spring at the other



Material Input Data: NiTi Wire Example

Stress [MPa]	As-Received Martensite Strain	As-Received Austenite Strain	10th Cycle Martensite Strain	10th Cycle Austenite Strain
0	0.000	0	0.02	0
50	0.003	0.001	0.029	0.001
100	0.020	0.002	0.033	0.002
150	0.028	0.003	0.034	0.003
200	0.032	0.004	0.035	0.004
250	0.035	0.005	0.036	0.005
300	0.037	0.006	0.037	0.006
400	0.040	0.008	0.04	0.008
500	0.042	0.011	0.041	0.01



Wire Design Tool[28]

- Required Input Parameters for Wire Design Tool

Name	Unit	Type	Description and range for input	Reset value	Symbol
OneWayLength	mm	Input: wire	>0, length of one or more wires mechanically in series	100	L
Diameter	mm	Input: wire	>0, wire diameter	0.25	d
# of ParallelWires	unit	Input: wire	>0, # of mechanically parallel wires	1	n
DispM_Bias_Met	mm	Input: system	>0, displacement where martensite curve and linear bias spring intercepts	5% of L	D_{int}
SpringConstant	N/mm	Input: system	Must be a number	1	k
ColdStop	mm	Input: system	Wire stop position at cold	D_{int}	D_{cold}
TargetStroke	mm	Input: system	>0, total motion amount left of minimum of D_{int} or D_{cold}	2% of L	D
Volume	mm³	Output	--	----------	V
MaxWireStress	MPa	Output	Maximum stress the wire experiences	----------	S_{max}

```
Intercept of M and Bias: strain=    0.0500
    stress(Mpa)=     172.2
Intercept of A and Bias: strain=    0.0053
    stress(Mpa)=     263.3
Relative to min of ColdStop & DispM_Bias_Met, extra strain is    0.0247

Intercept of M and Bias: disp(mm)=      5.00
    load(N)=      8.5
Intercept of A and Bias: disp(mm)=      0.53
    load(N)=      12.9
Relative to min of ColdStop & DispM_Bias_Met, extra stroke(mm) is
2.47

Solution strain=     0.0300
Solution stress(Mpa)=     212.9
Strain @ Max wire stress=     0.0300
Max wire stress(Mpa)=     212.9

Solution disp(mm)=      3.00
Solution load(N)=      10.5
Disp(mm) @ Max wire stress=      3.00
Max wire load(N)=      10.5

Predicted Life=    333038 cycles
```

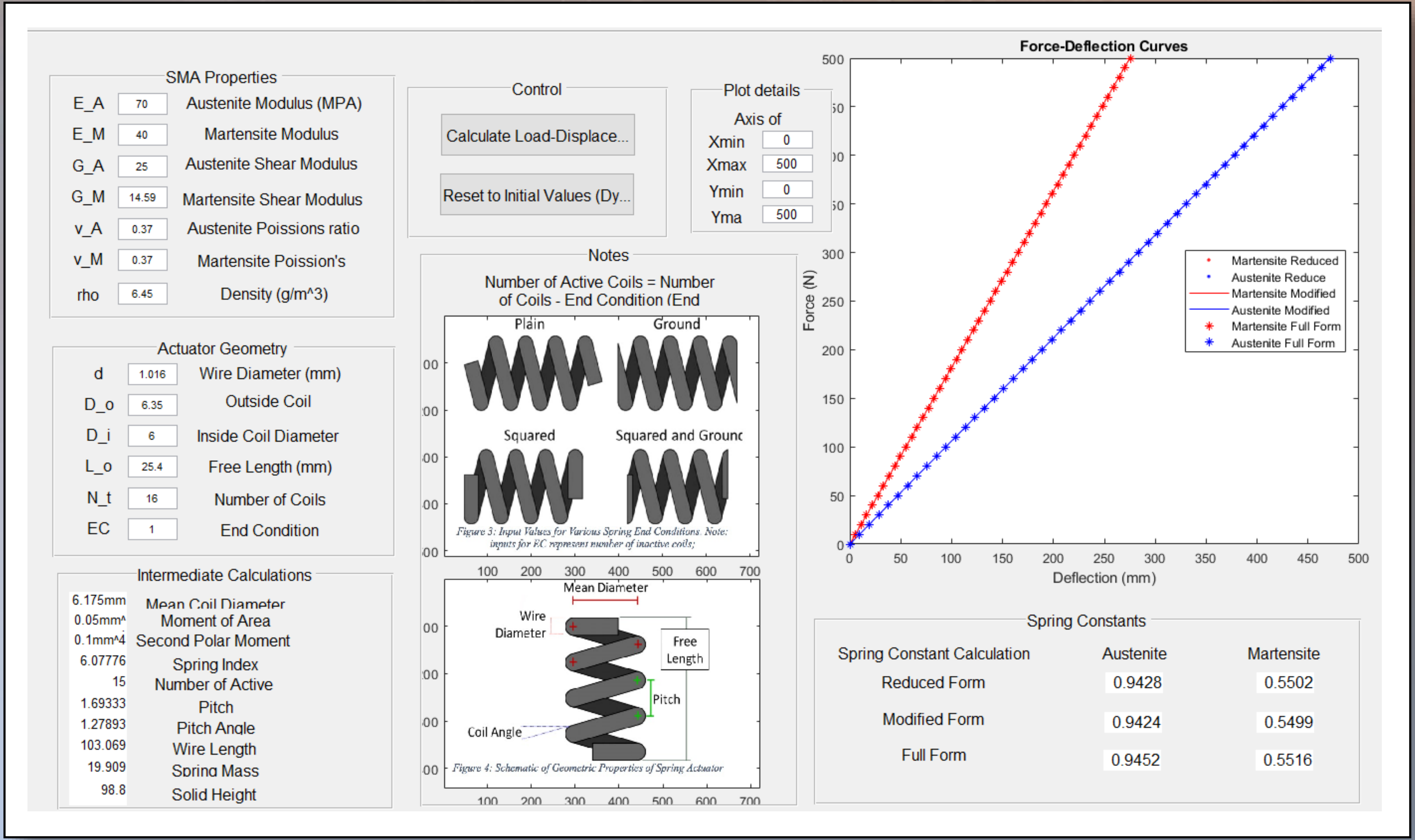
- Example output or solution message of the wire design tool

Wire Design Tool

Wire Design Tool[28]

- Input parameters that describe the material and actuator application
- Output deflection and stress in austenite and martensite as a function of applied load

Solve for strokes, loads, as a function of geometries

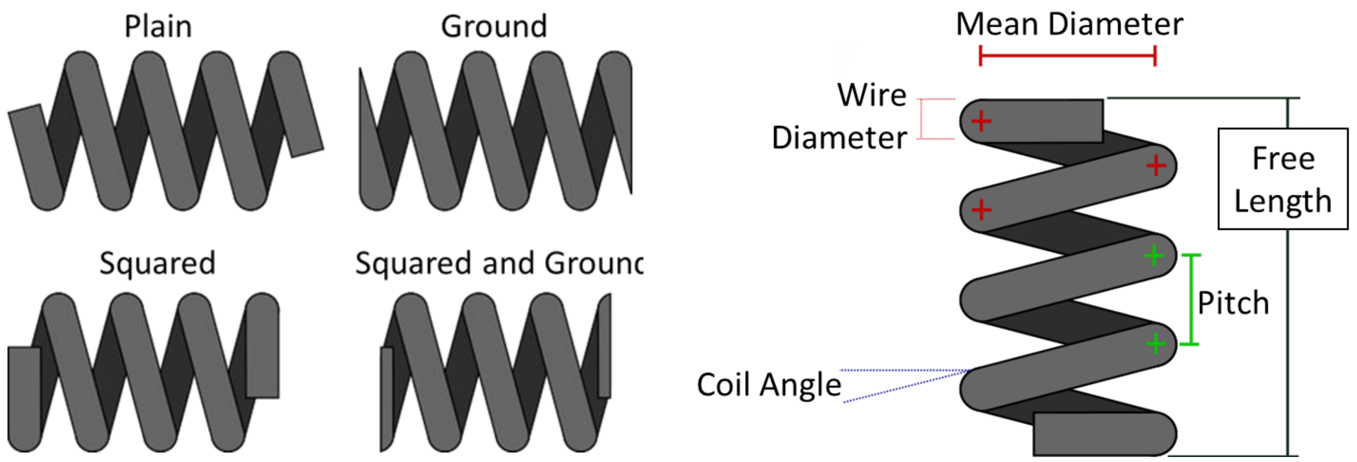


Wire Design Tool[28]

- Input parameters that describe the material and actuator application
- Output deflection and stress in austenite and martensite as a function of applied load

Required input parameters

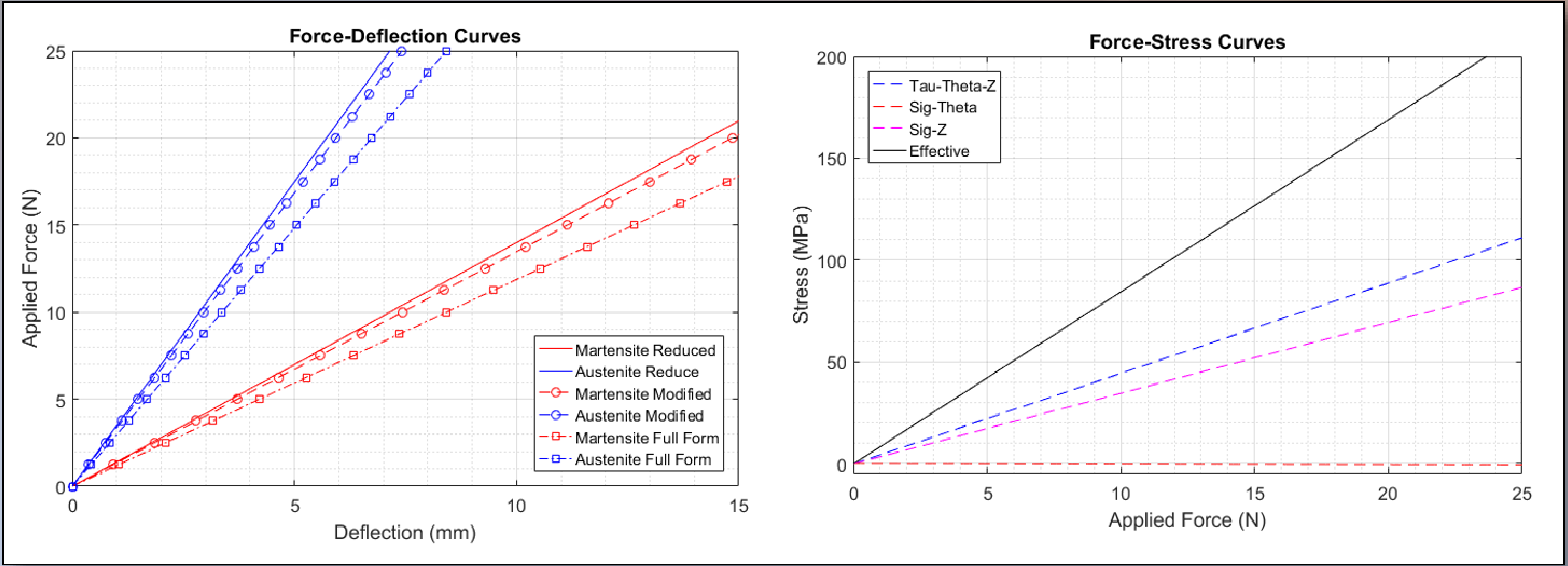
Input value	Input unit	Input type	Symbol
Wire diameter	mm	Spring geometry	d
Mean coil diameter	mm	Spring geometry	D
Free length	mm	Spring geometry	L_o
Number of coils	------------	Spring geometry	N_t
End condition	------------	Spring geometry	EC
Shear modulus	GPa	Material property	G_A, G_M
Young's modulus	GPa	Material property	E_A, E_M
Poisson's ratio	------------	Material property	v_A, v_M
Density	g/cm³	Material property	ρ
Applied force	N	Actuator property	F
Load evolution	N/mm	Actuator property	ΔF
Cold position	mm	Actuator property	x_M



Input values for various spring end conditions. (a) Plain. (b) Ground. (c) Squared. (d) Squared and ground.

Wire Design Tool[28]

Graphical Output



(a) Force-deflection curves.

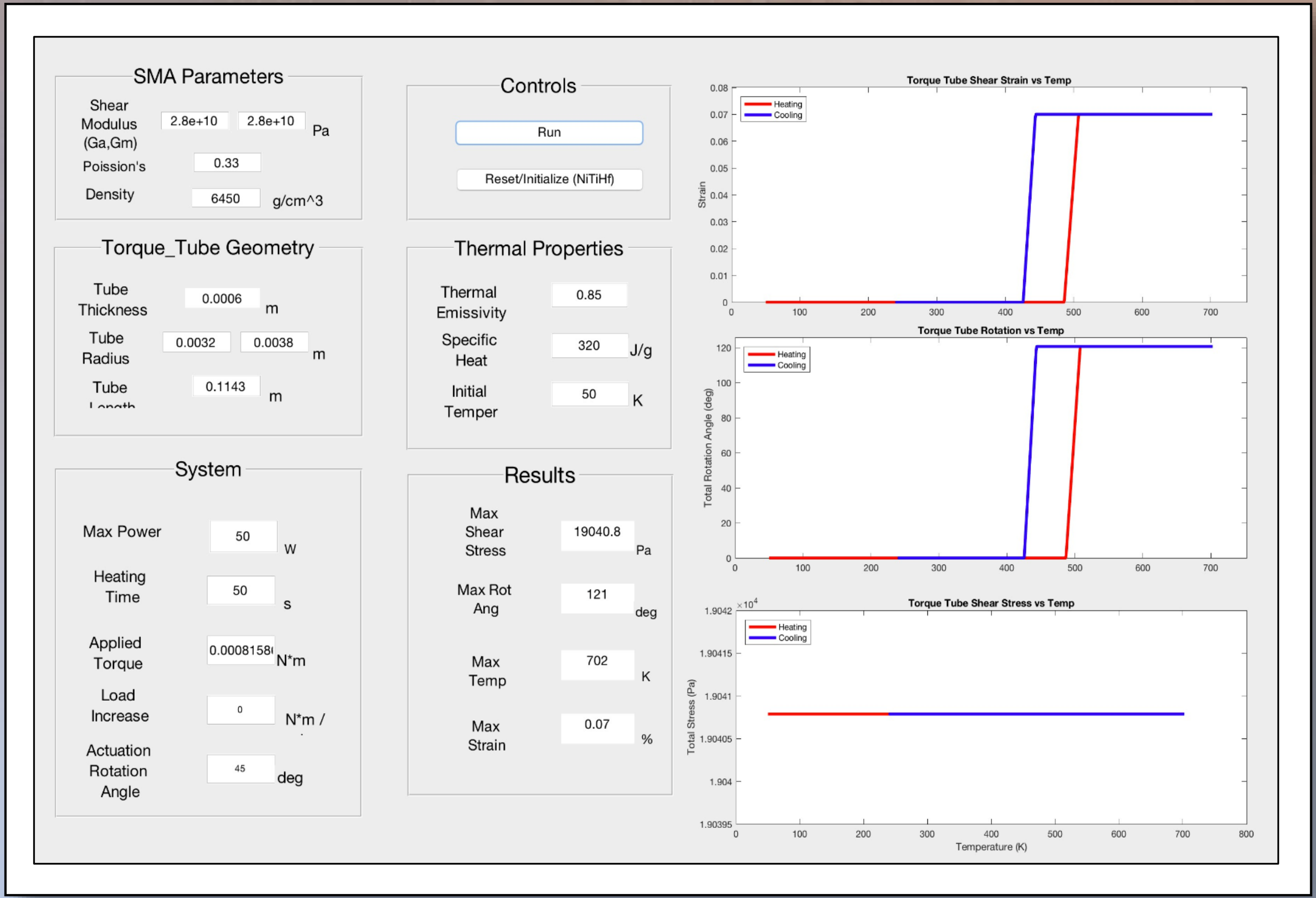
(b) Force-stress curves.

Spring Design Tool

Torque Tube Design Tool[28]

- GUI-based version to predict the actuation stroke
- Code-based version that utilizes a design of experiments (DoE) to select an optimal torque tube design

Solve for strokes, loads, as a function of geometries



Torque Tube Tool[28]

- GUI-based version to predict the actuation stroke
- Code-based version that utilizes a design of experiments (DoE) to select an optimal torque tube design

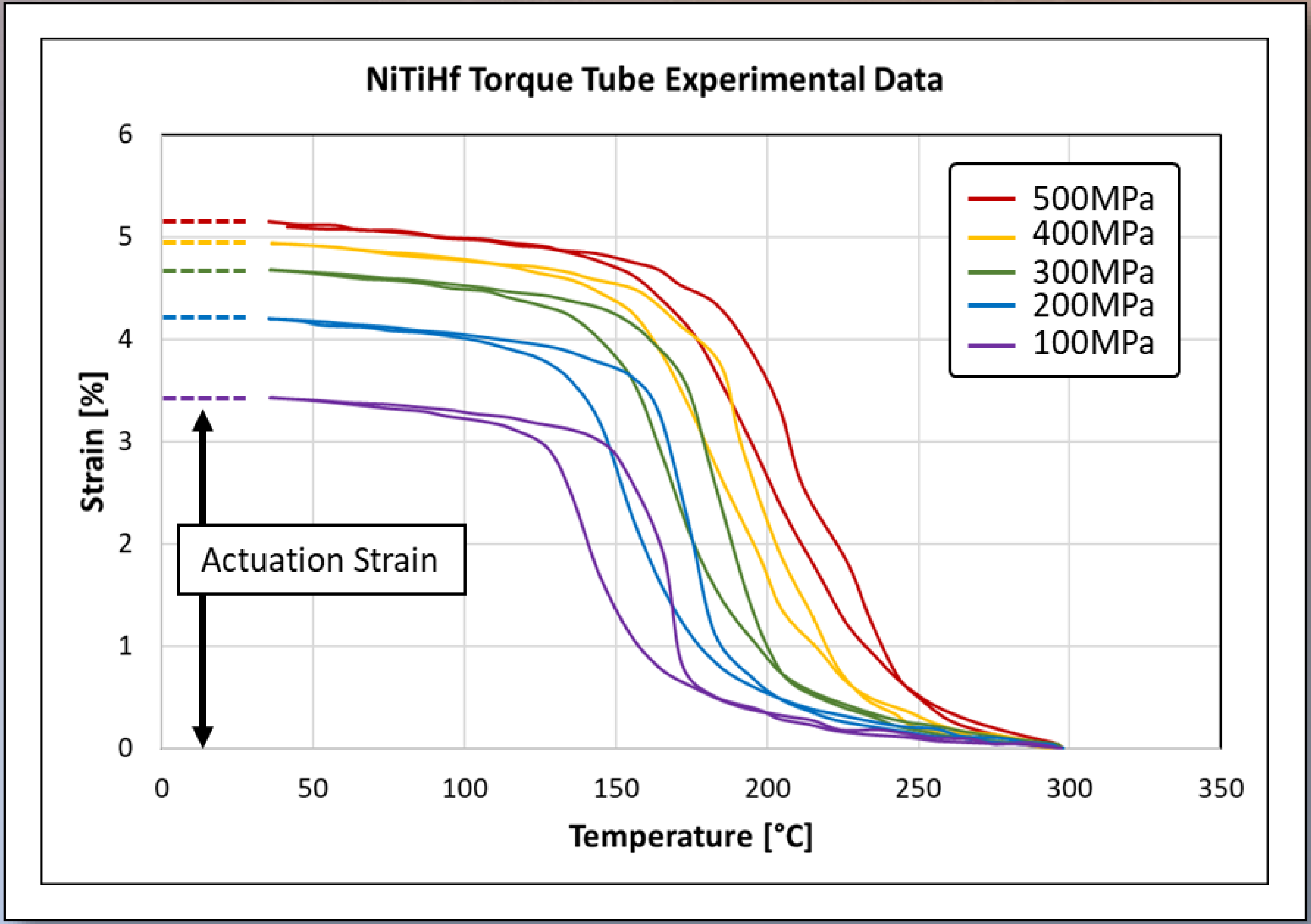
Required input parameters

Input value	Input unit	Input type	Symbol
Tube thickness	mm	Tube geometry	t
Tube radius	mm	Tube geometry	R
Tube length	mm	Tube geometry	L
Available power	W	System	P
Heating time	s	System	$time_{heat}$
Applied torque	N·m	System	$Torque_{app}$
Load increase	(N·m)/deg	System	$\Delta Torque$
Shear moduli	GPa	Material property	G_A, G_M
Minimum transformation strain	mm/mm	Material property	H_{min}
Maximum transformation strain	mm/mm	Material property	H_{sat}
Transformation strain evolution parameter	--------------	Material property	k
Poisson's ratios	--------------	Material property	υ_A, υ_M
Density	g/cm^3	Material property	ρ
Transformation temperatures	K	Material/thermal property	M_f, M_s, A_f, A_s
Transformation temperature evolution	K/MPa	Material/thermal property	C_M, C_A
Thermal emissivity	--------------	Thermal property	e
Initial temperature	K	Thermal property	T_e
Specific heat	J/g	Thermal property	c
Heating increment	s	Modeling setting	Δt

Torque Tube Tool[28]

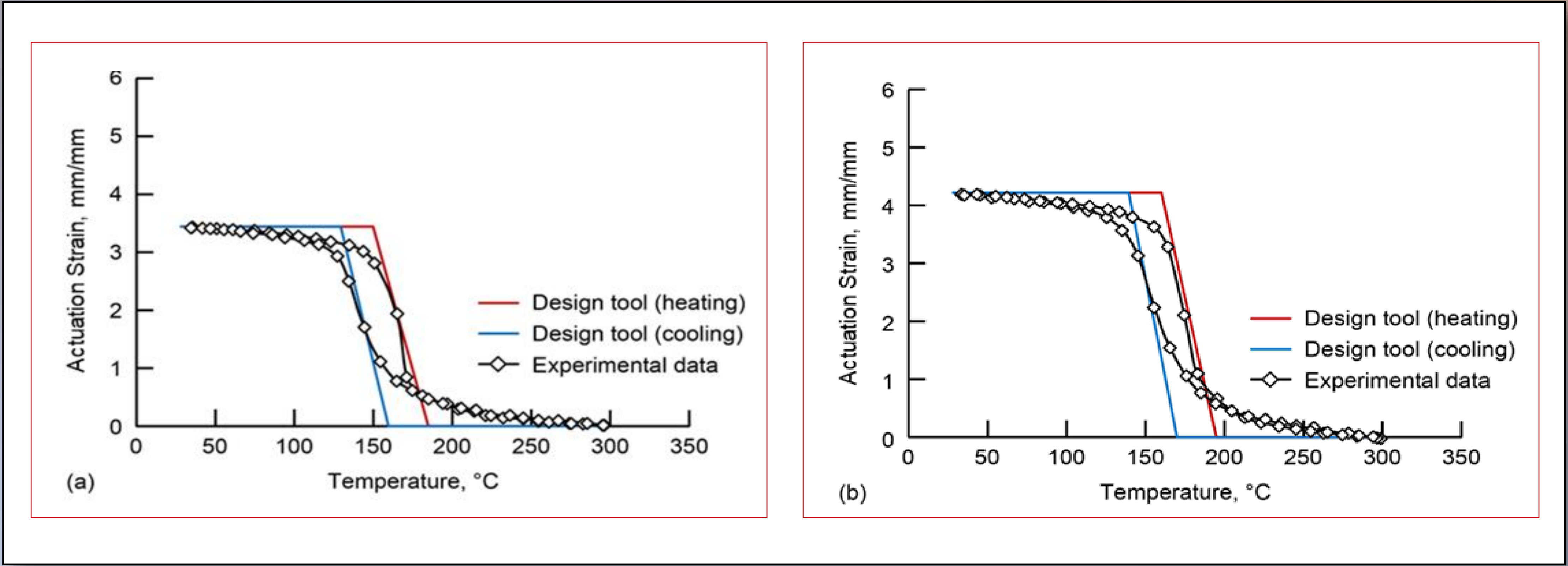
- GUI-based version to predict the actuation stroke
- Code-based version that utilizes a design of experiments (DoE) to select an optimal torque tube design

Torque Tube Calibration Data (NiTiHf)



Torque Tube Tool[28]

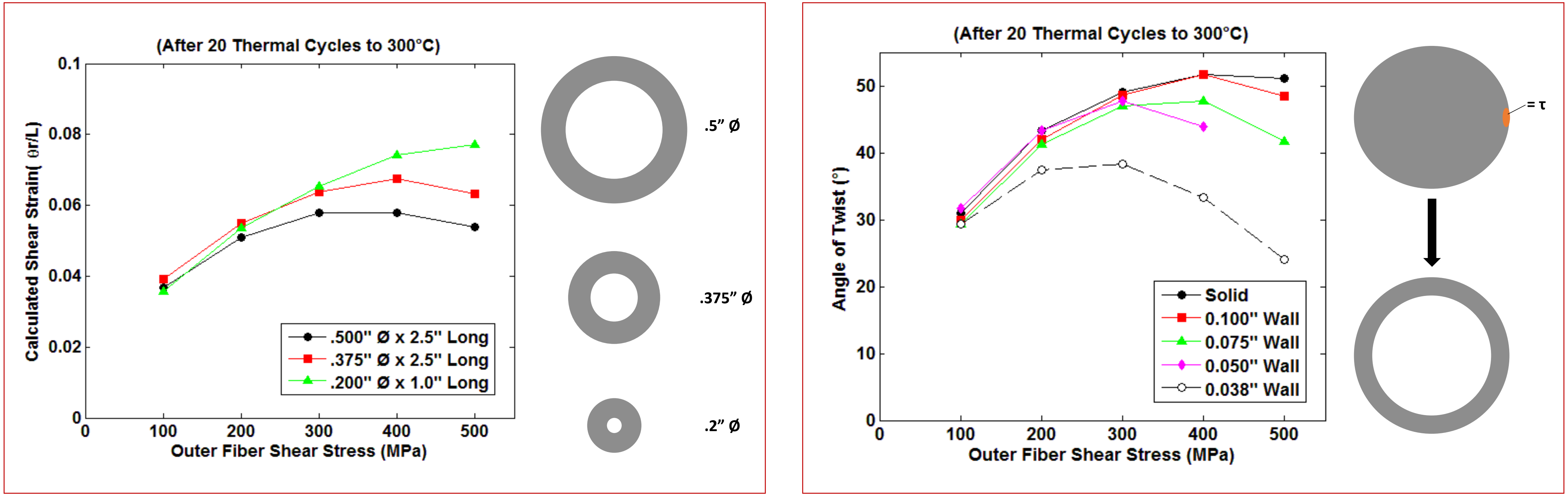
Graphical Output



Simulated actuation strain from torque tube modeling tool calibration compared with experimental results.

Torque Tube Tool[28]

Tube Sizing



Torque Tube Design Tool

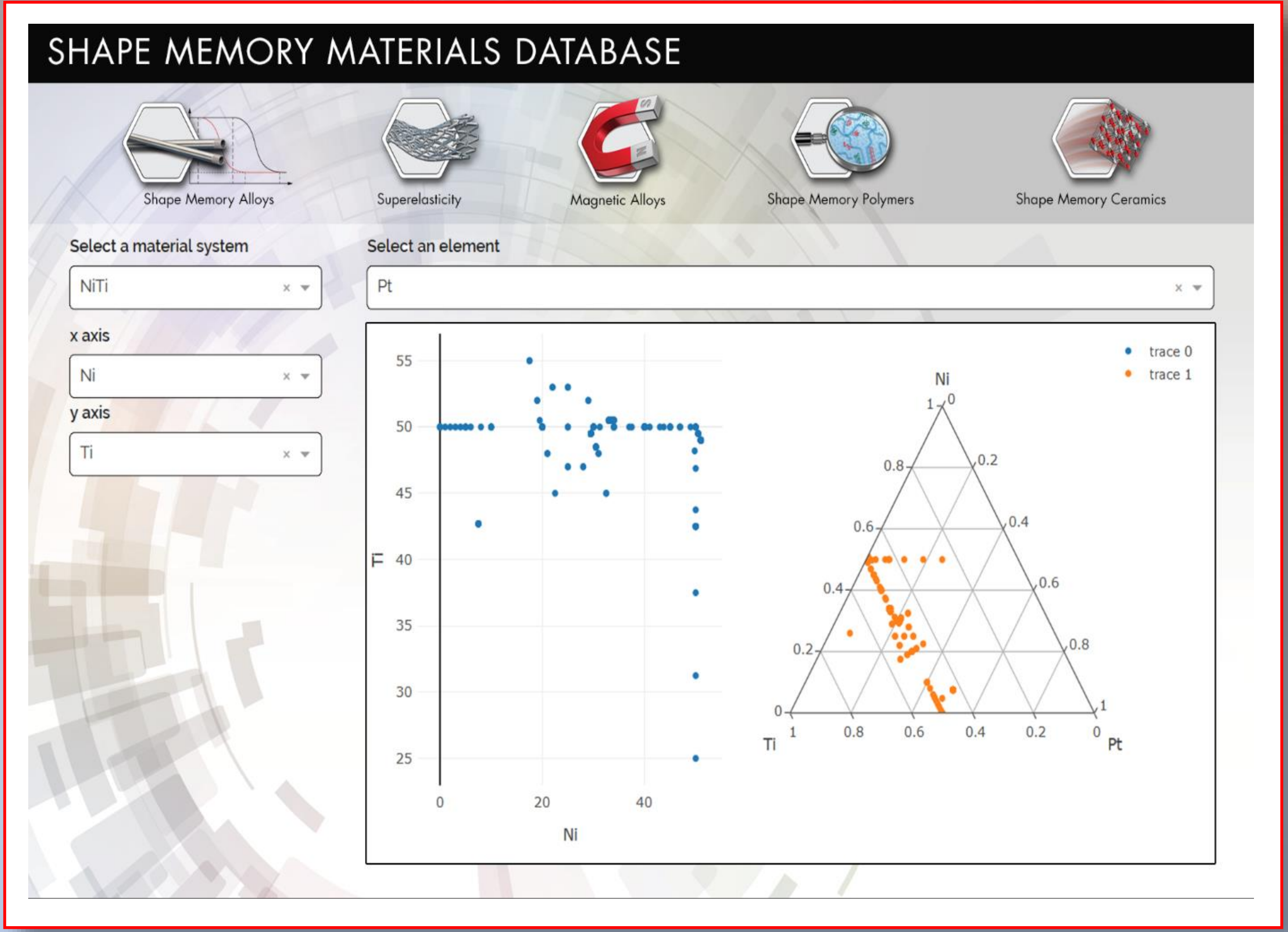
Are you looking for what material to use?

Temperature?

Strains?

Cost?

Look no more, the Shape Memory Material Database is here for you.

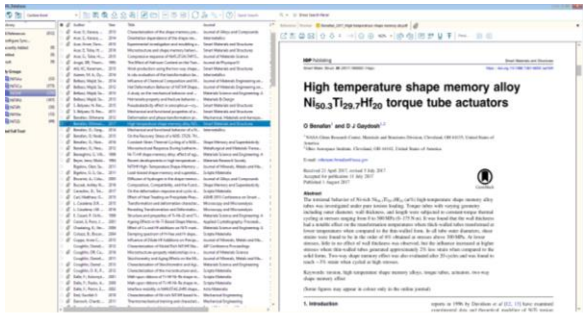


Shape Memory Material Database, how does it work?

1. Collect

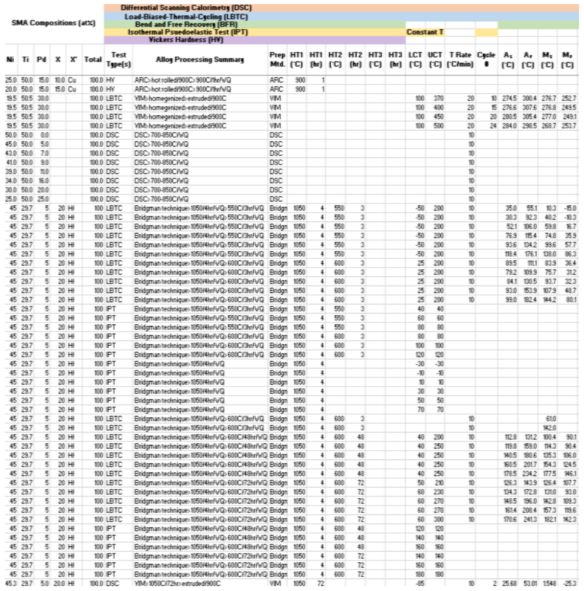
Collect and organize all existing publications for Shape memory materials (SMM)

- Belyaev_2015_Pseudoelasticity effect in amorphous—crystalline Ti 40.7 Hf 9.5 Ni 44.8 Cu 5 shape mem...
- Benafan_2012_Deformation and phase transformation processes in polycrystalline NiTi and NiTiHf hig...
- Benafan_2012_Microstructural Response During Isothermal and Isobaric Loading of a Precipitation-Str...
- Benafan_2014_Mechanical and functional behavior of a Ni-rich Ni50.3Ti29.7Hf20 high temperature sh...
- Benafan_2015_On the Recovery Stress of a Ni50. 3Ti29. 7Hf20 High Temperature Shape Memory Alloy
- Benafan_2016_Constant-Strain Thermal Cycling of a Ni50.3Ti29.7Hf20 High-Temperature Shape Mem...
- Benafan_2017_High temperature shape memory alloy Ni50.3Ti29.7Hf20 torque tube actuators
- Besseghini_1999_Ni-Ti-Hf shape memory alloy effect of aging and thermal cycling
- Beyer_1995_Recent developments in high temperature shape memory alloys
- Bigelow_2011_Load-biased shape-memory and superelastic properties of a precipitation strengthened...
- Biscarini_2005_Diffusion of hydrogen in the shape memory alloy Ni47Ti40Hf10Cu3



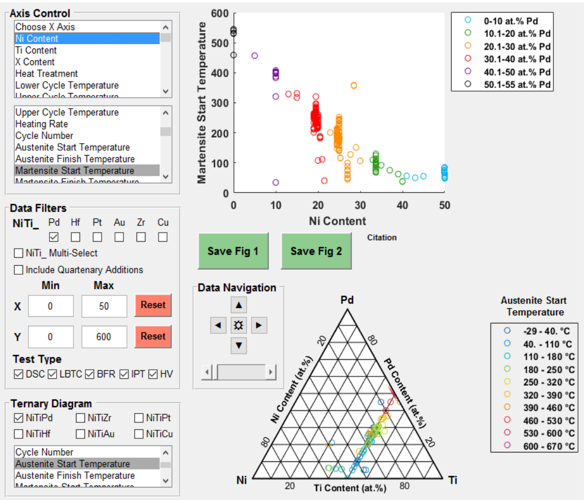
2. Extract

Extract and consolidate data from literature into a standard-format.

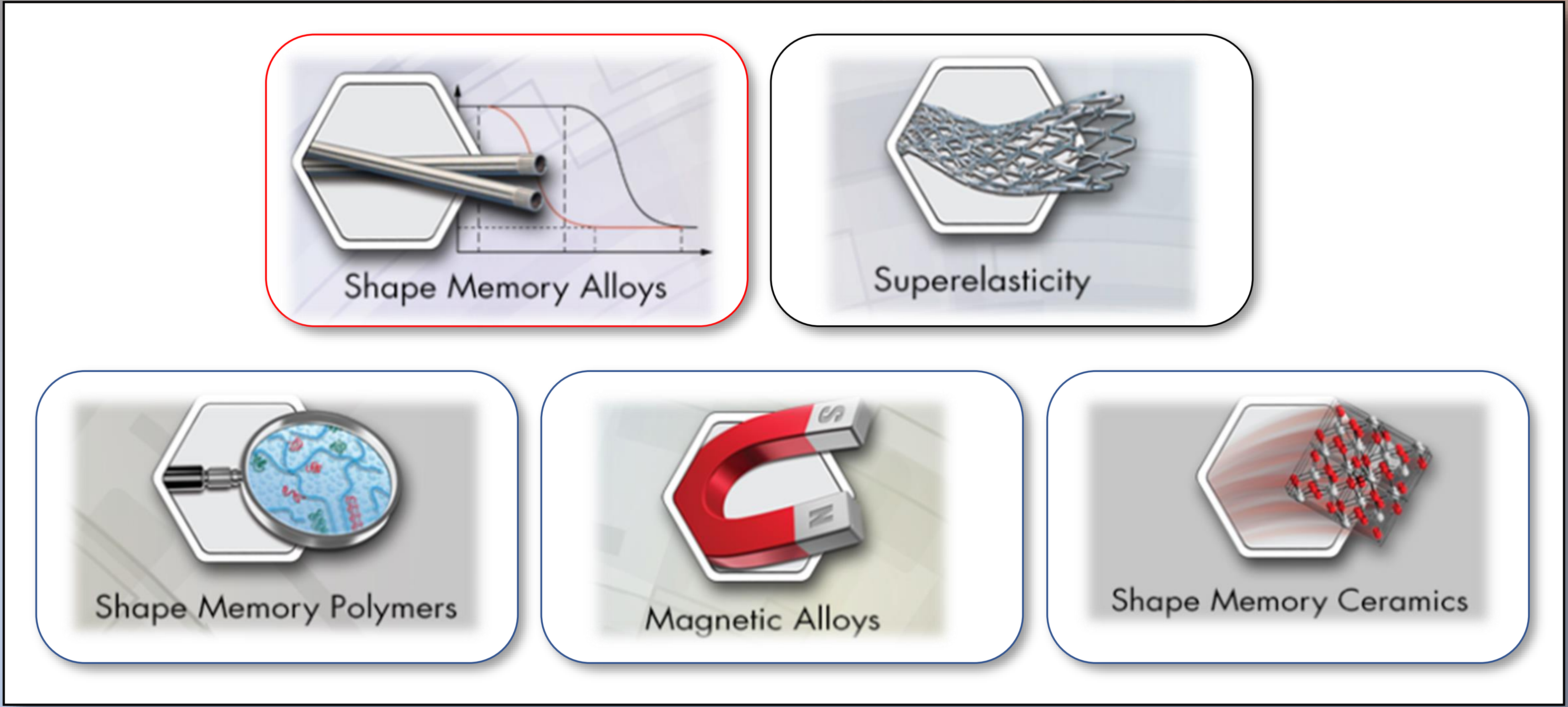


3. Design

Integrate data into a graphical user interface (GUI) to explore the SMM system.



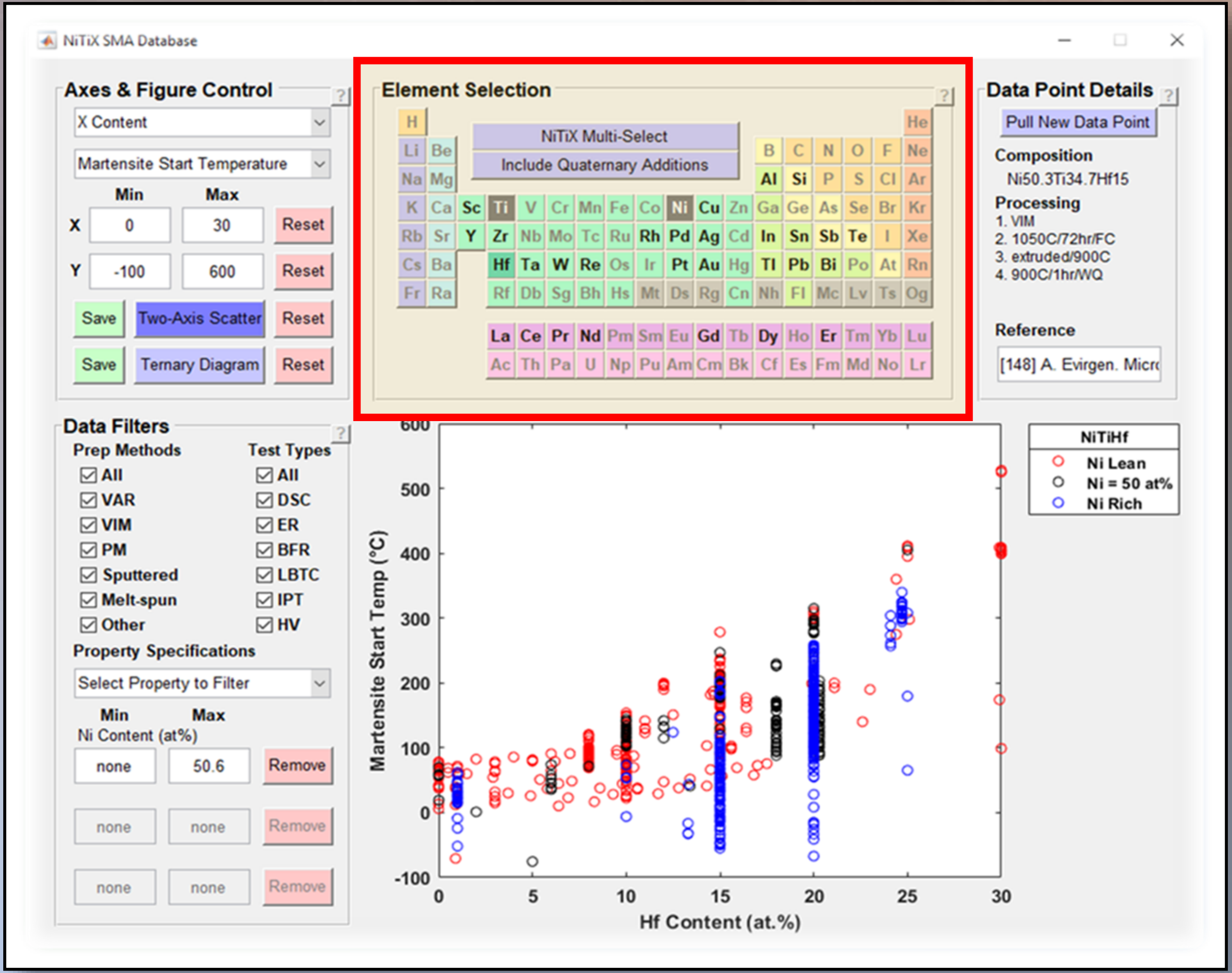
Shape Memory Material Database, select a material system.



Shape Memory Material Database, Example: Alloys

Select an alloy (or multiple) from the periodic table)

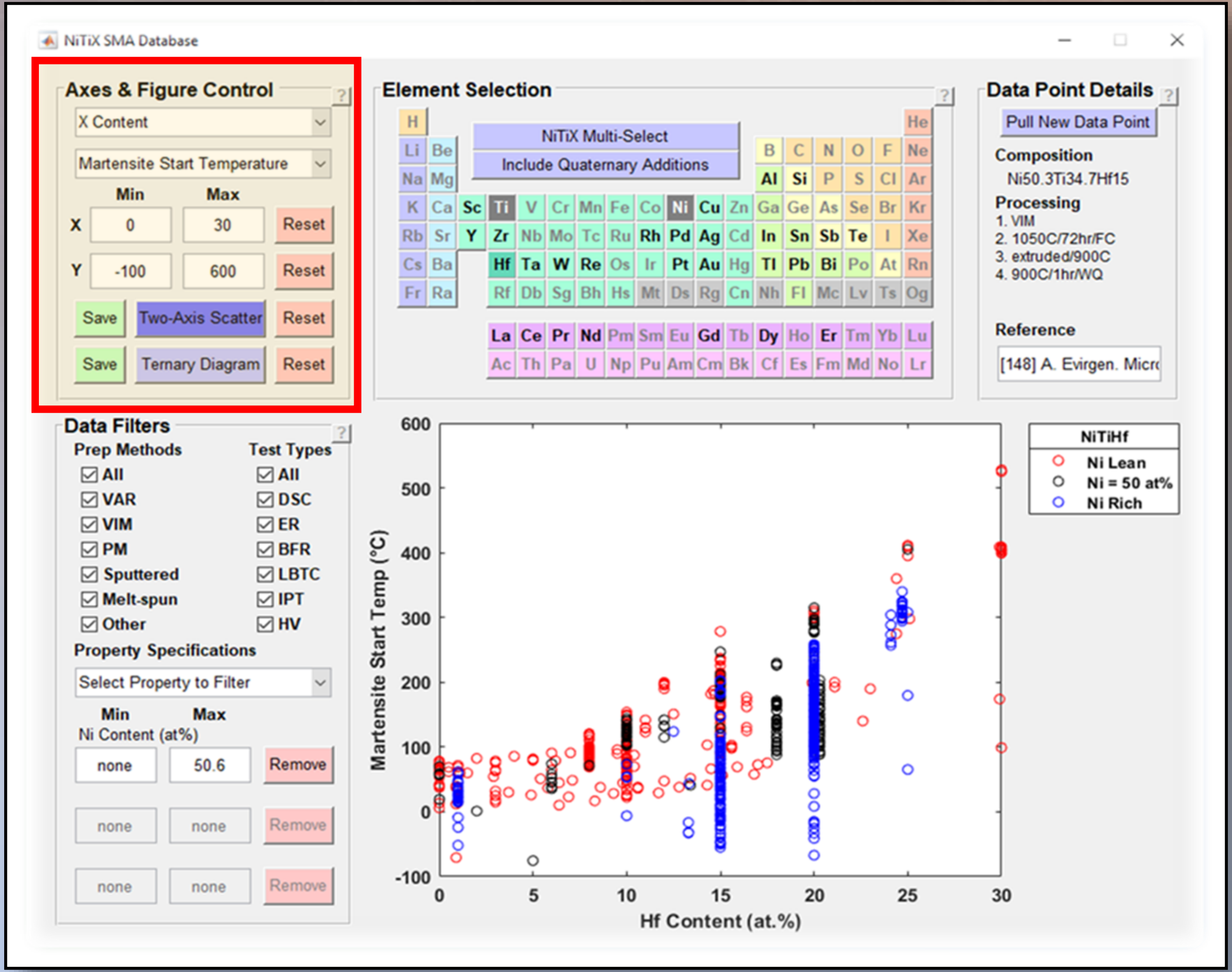
- Can consider weight
- Cost
- Processability



Shape Memory Material Database, Example: Alloys

Select properties of interest to examine (binary or ternary plot)

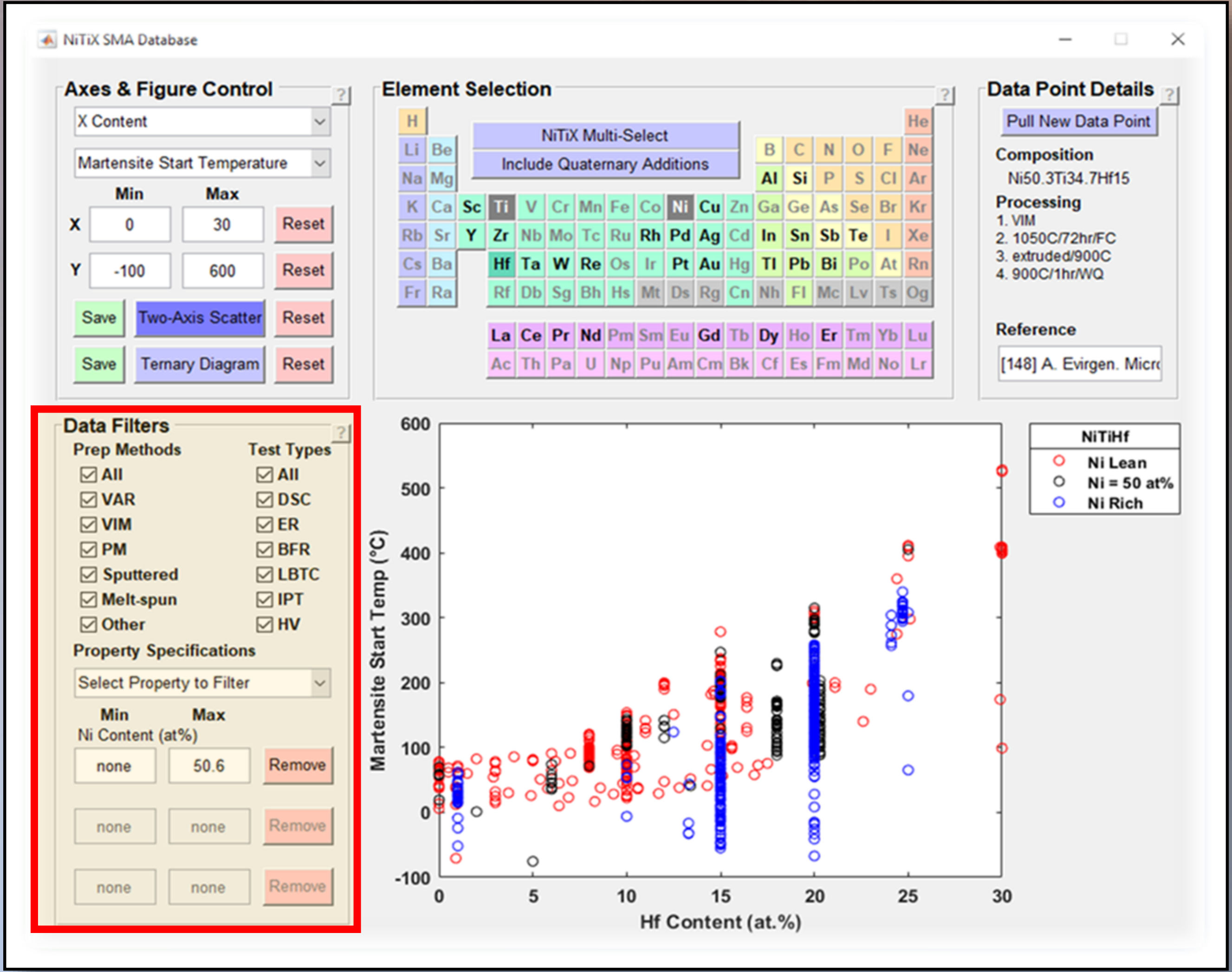
- Transformation temperatures
- Yield strength/strains
- Hardness



Shape Memory Material Database, Example: Alloys

Apply filters to narrow search

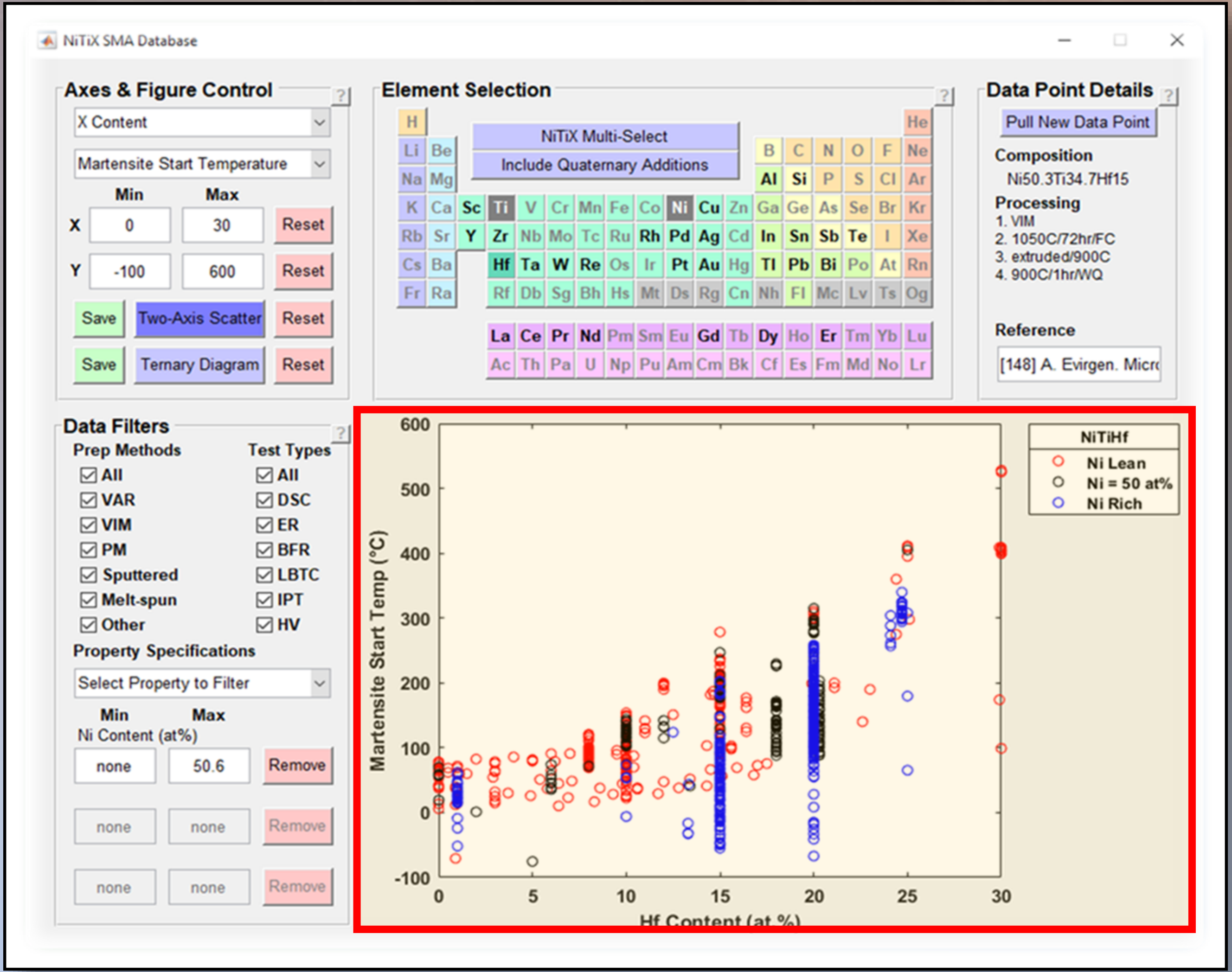
- Processing methods
- Types of loading (torsion, tension, compression)
- Ranges



Shape Memory Material Database, Example: Alloys

Get all the data you need

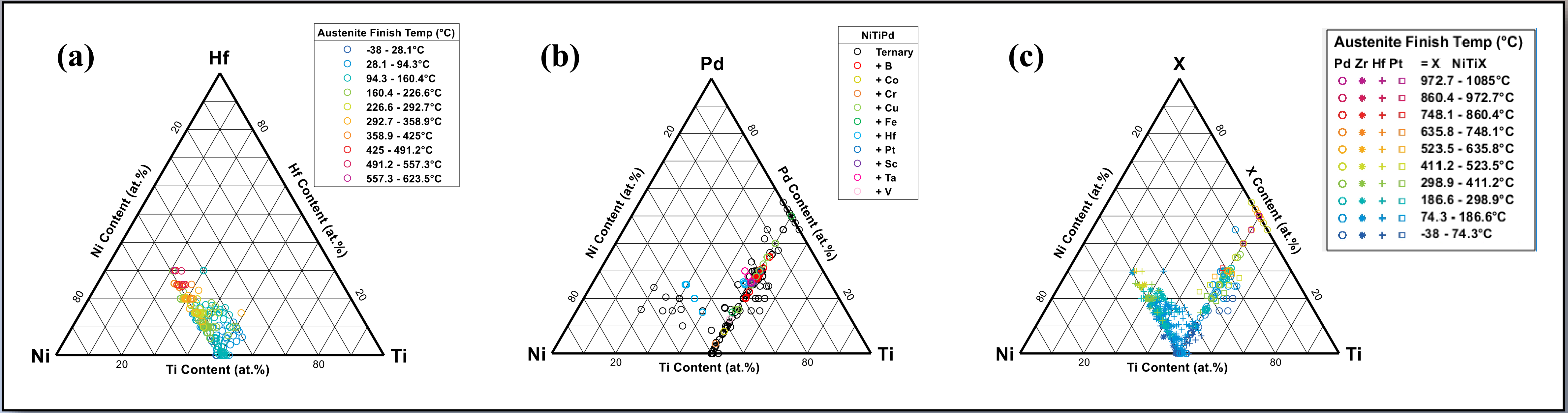
- Plot trends
- Hover around data points for source information
- Output data



Shape Memory Material Database, Ternary Diagrams:

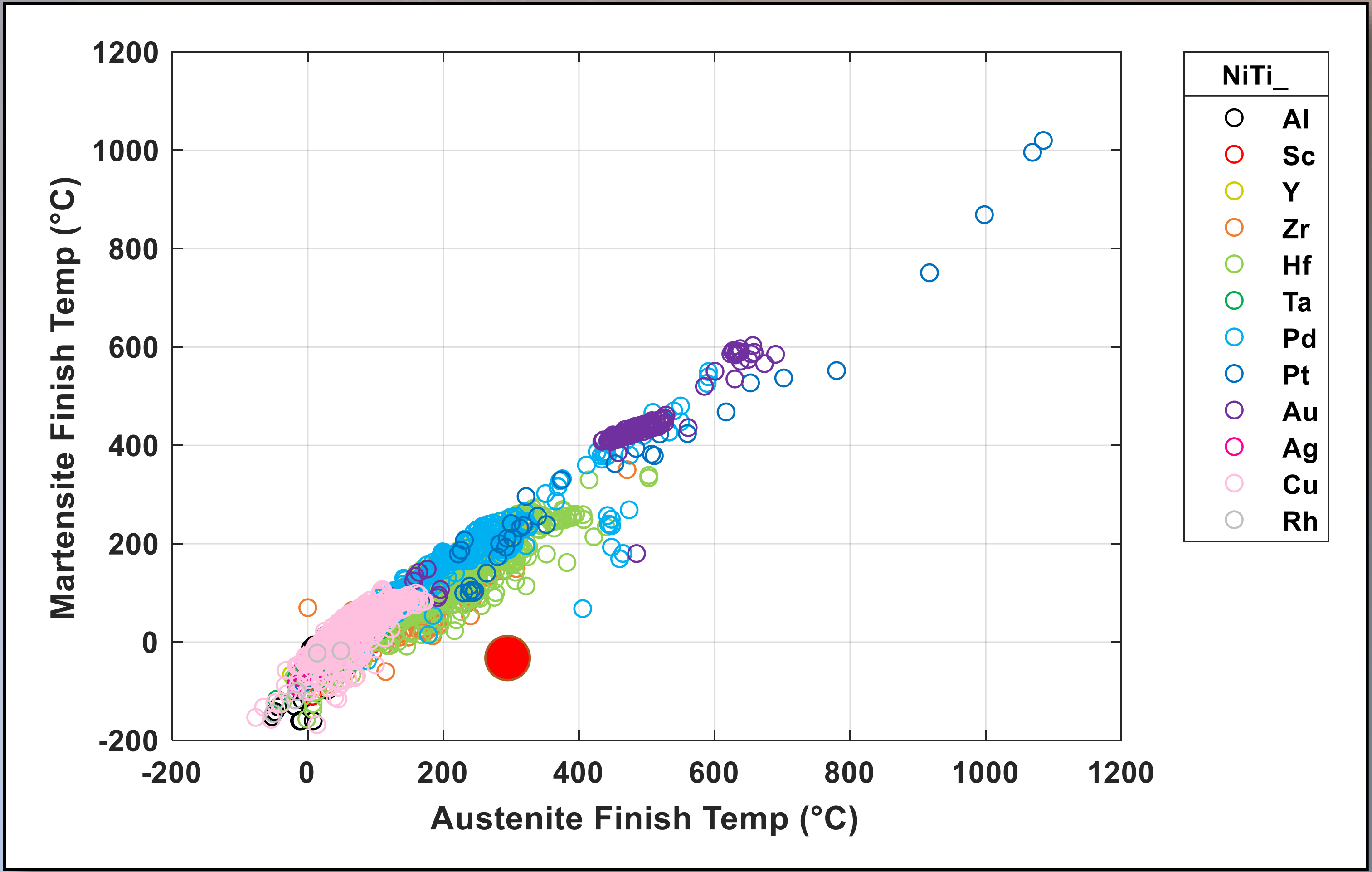
Ternary diagrams:

a) Plotting a single ternary SMA system
b) Plotting quaternary SMAs
c) Plotting multiple ternary SMA systems at once



Shape Memory Material Database, Case Study:

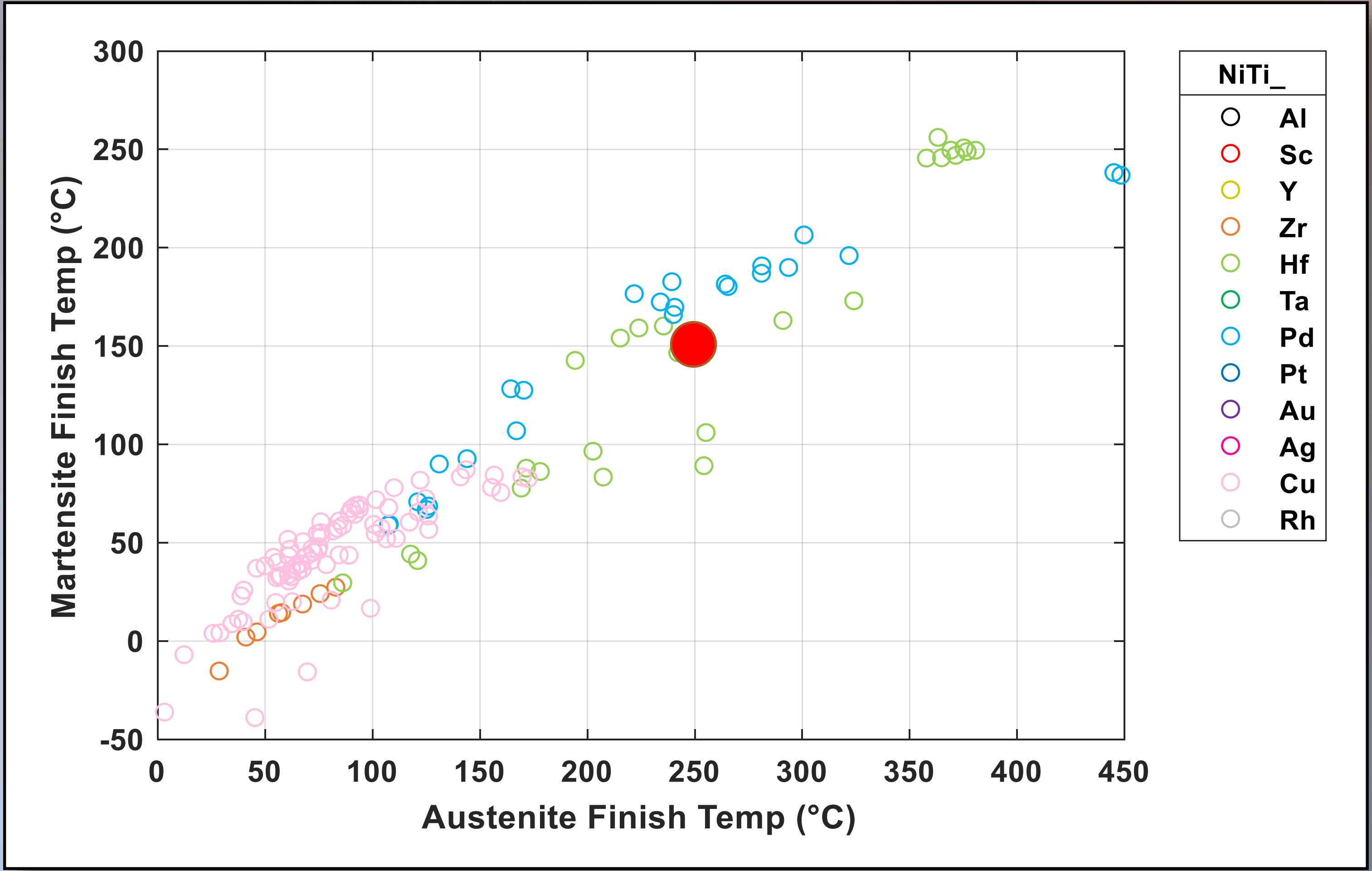
a) I need a material with an austenite finish temperature of 250 °C and a martensite finish temperature of 150 °C.



Shape Memory Material Database, Case Study:

a) I need a material with an austenite finish temperature of 250 °C and a martensite finish temperature of 150 °C.

b) I need actuation strains of ~4 to 6%.

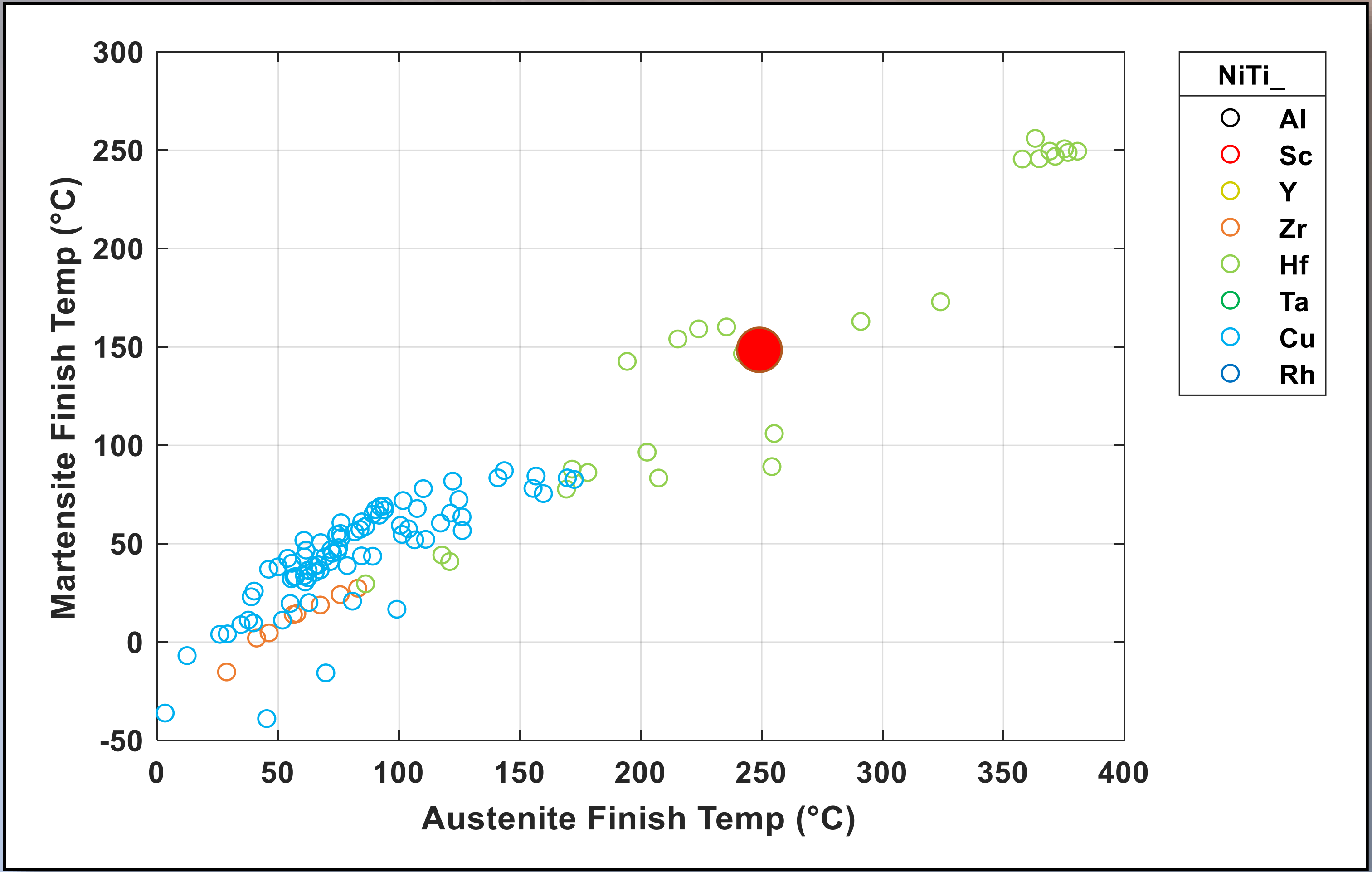


Shape Memory Material Database, Case Study:

a) I need a material with an austenite finish temperature of 250 °C and a martensite finish temperature of 150 °C.

b) I need actuation strains of ~4 to 6%.

c) Cannot afford precious metals.



Shape Memory Material Database, Web Tool

a) Access to this tool will be publicly available on or before September 2018.

b) If interested, contact othmane.benafan@nasa.gov.

Choosing the right material for the right applications

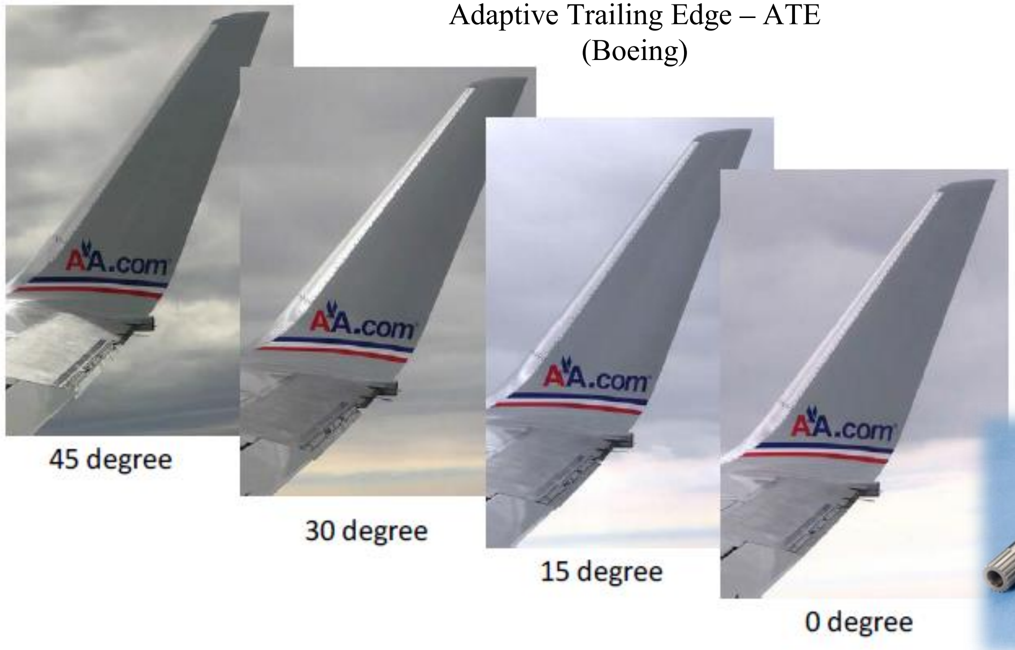
High Temperature Shape Memory Alloys (HTSMAs)

Control surfaces

Spanwise adaptive wing

PLAY

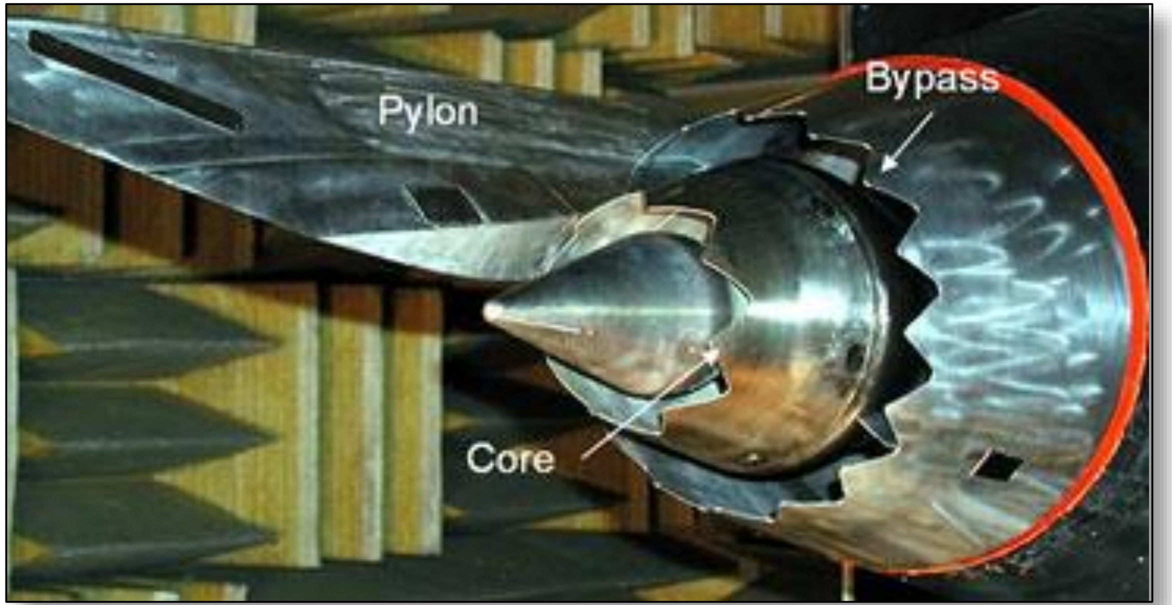
Adaptive Trailing Edge – ATE
(Boeing)



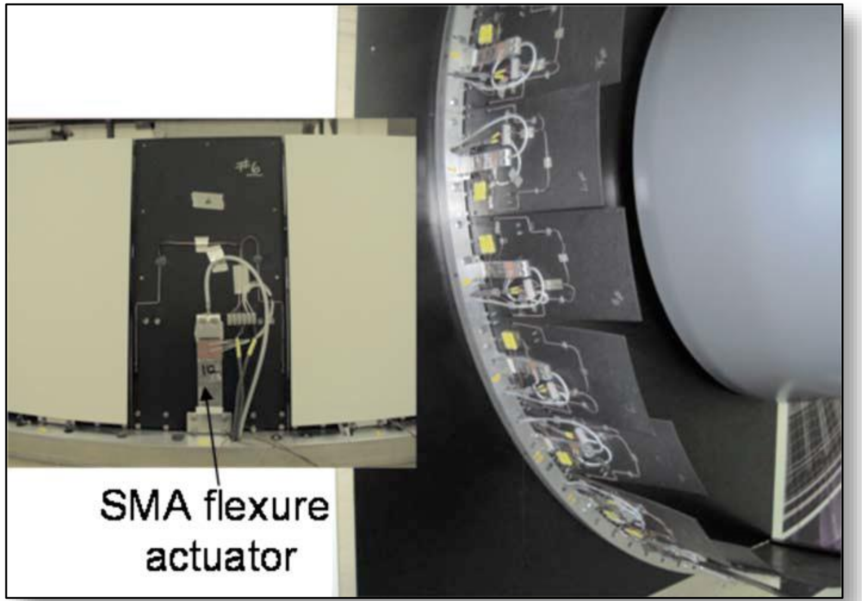
Choosing the right material for the right applications

High Temperature Shape Memory Alloys (HTSMAs)

Engines



Active Jet Engine Chevron (LaRC)



Variable Area Fan Nozzles (Boeing)

Choosing the right material for the right applications

High Temperature Shape Memory Alloys (HTSMAs)

Shape Memory Alloy Rock Splitters (SMARS)— When SMAs meet rocks

R&D 100
55 Years of Invention

R&D 100
55 Years of Invention

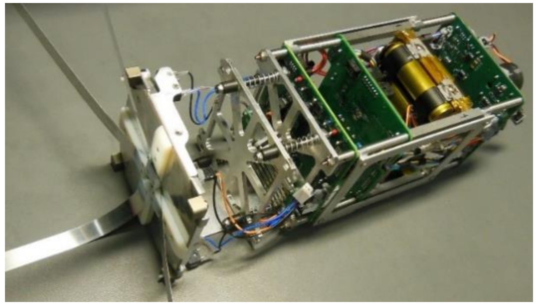
PLAY

Choosing the right material for the right applications

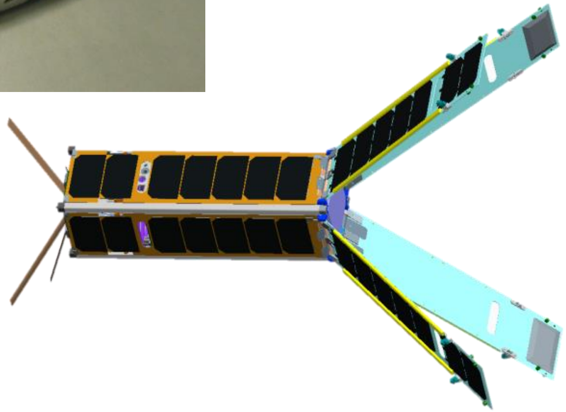
Low Temperature Shape Memory Alloys (LTSMAs)

Autonomous Actuation


Cold Space (Smallsats)



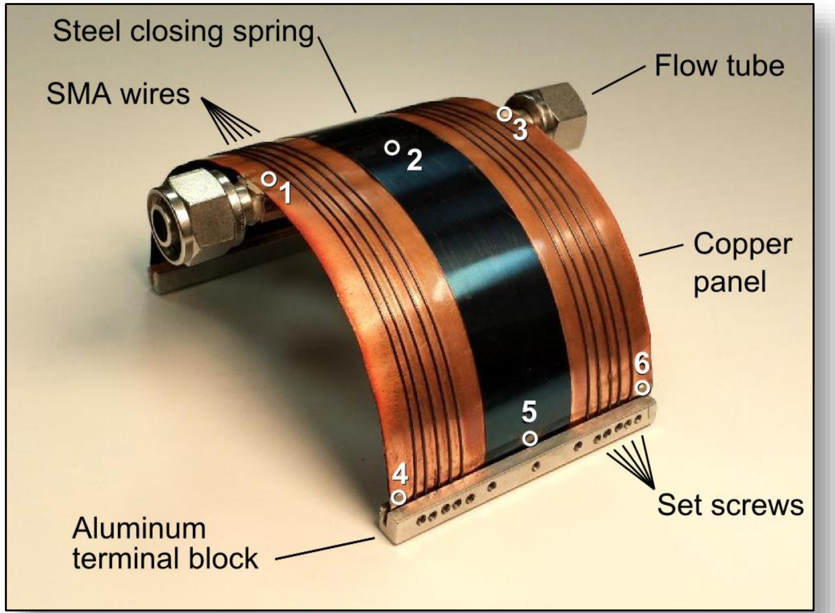
Pointing devices
Thermal switches
Deployment

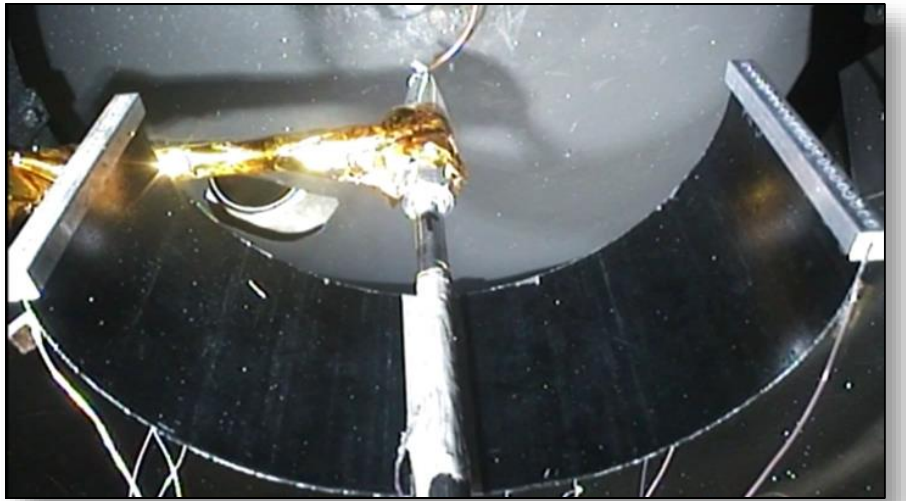


Choosing the right material for the right applications

Low Temperature Shape Memory Alloys (LTSMAs)

Composite Morphing Radiator (JSC)

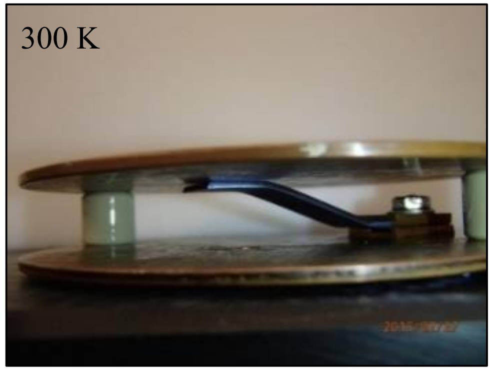


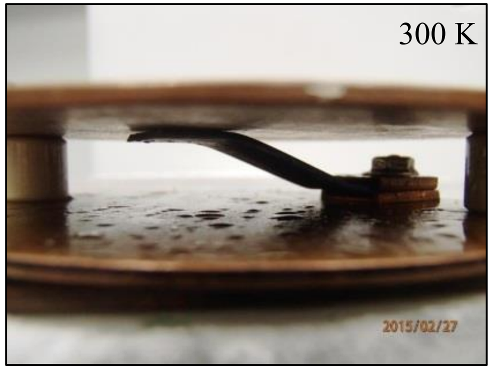


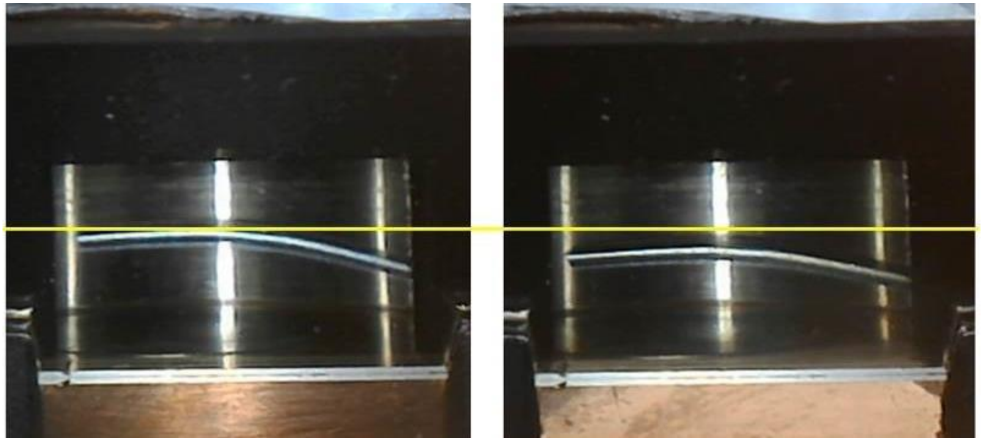
Choosing the right material for the right applications

Low Temperature Shape Memory Alloys (LTSMAs)

Adaptive Thermal Management System (KSC)







Choosing the right material for the right applications

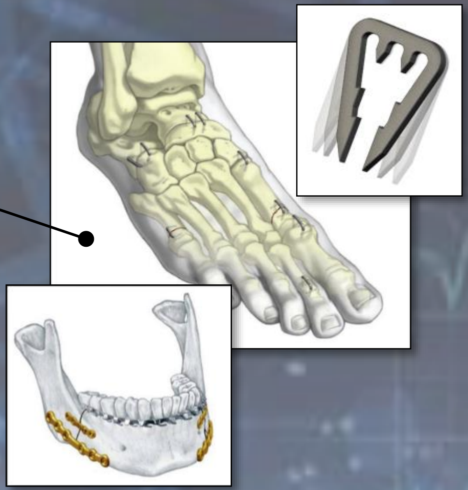
Superelastic alloys

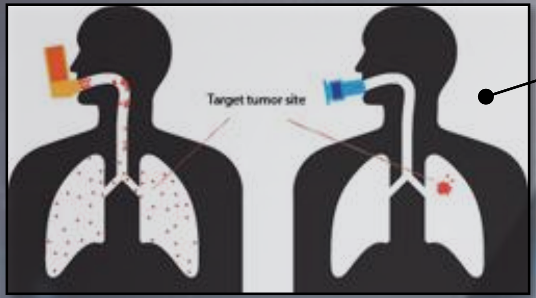
Tribology (Bearings and Gears)

Rover Tires

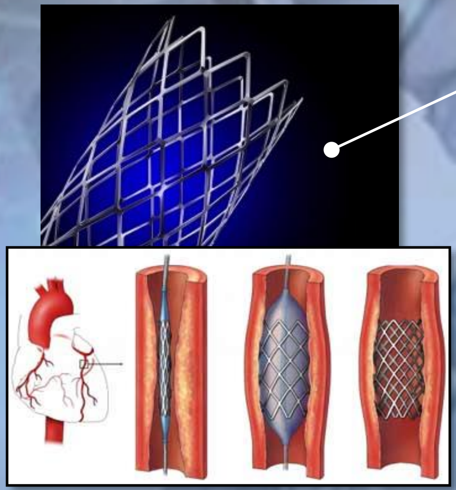
Application of Shape Memory Alloys | *Biomedical*

Implants
- Jaw Plates
- Bone Staples
- Hip Implants
- Pedicle Screws





Medical Devices
- Targeted Inhalers
- Catheter Tubes
- Instruments

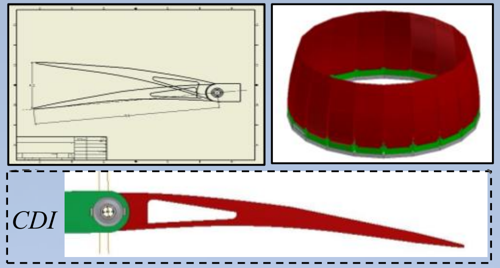


Stents

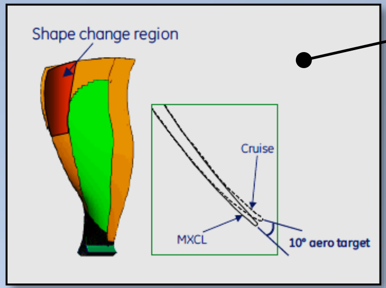
Consumer Products
- Eyeglasses
- Orthodontics

Application of Shape Memory Alloys | *Aeronautics*

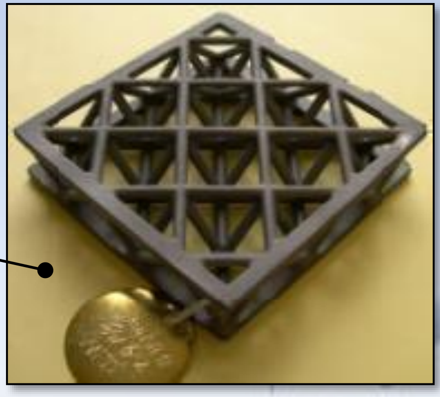
Variable Area Nozzle
- High bypass turbofan
- SMA torque tubes provide flap rotation
- Engine noise reduction



Adaptive Fan Blade
- Embedded SMA actuators
- Aerodynamic efficiency
- Specific fuel consumption reduction



SMA Cellular Structures
- Airframe and engine components
- Morphing airfoils
- Lightweight trusses

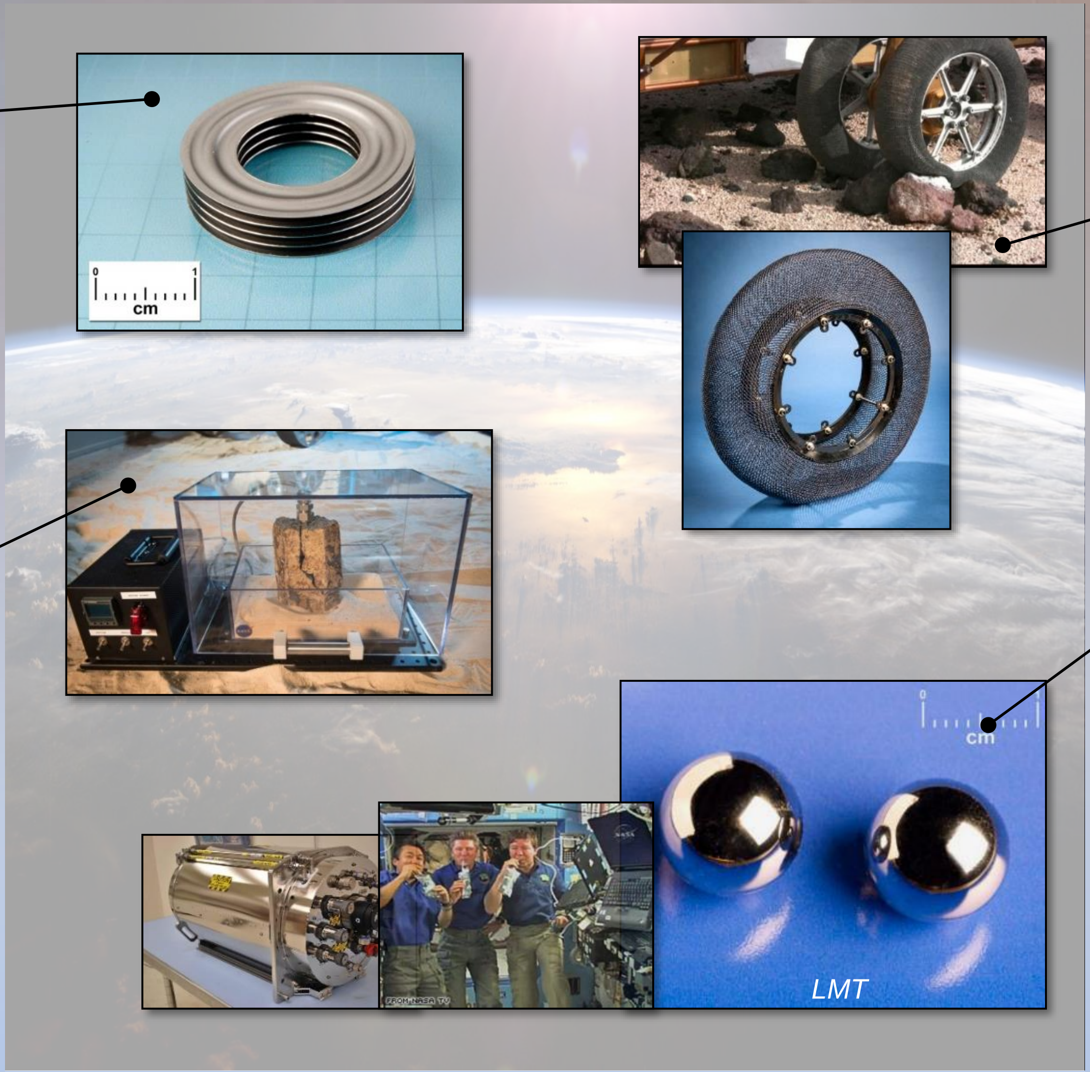


Variable Geometry Chevron
- SMA actuators morph the chevron
- Noise reduction at takeoff
- Shock cell noise reduction at cruise

Application of Shape Memory Alloys | *Space*

SMA Bellows
- Dynamic sealing
- Fluid handling
- Flexibility (structure alignment)

SMA rock splitters



SMA Spring Tire
- Superelastic technology
- Lunar and Martian rovers
- Non-Pneumatic

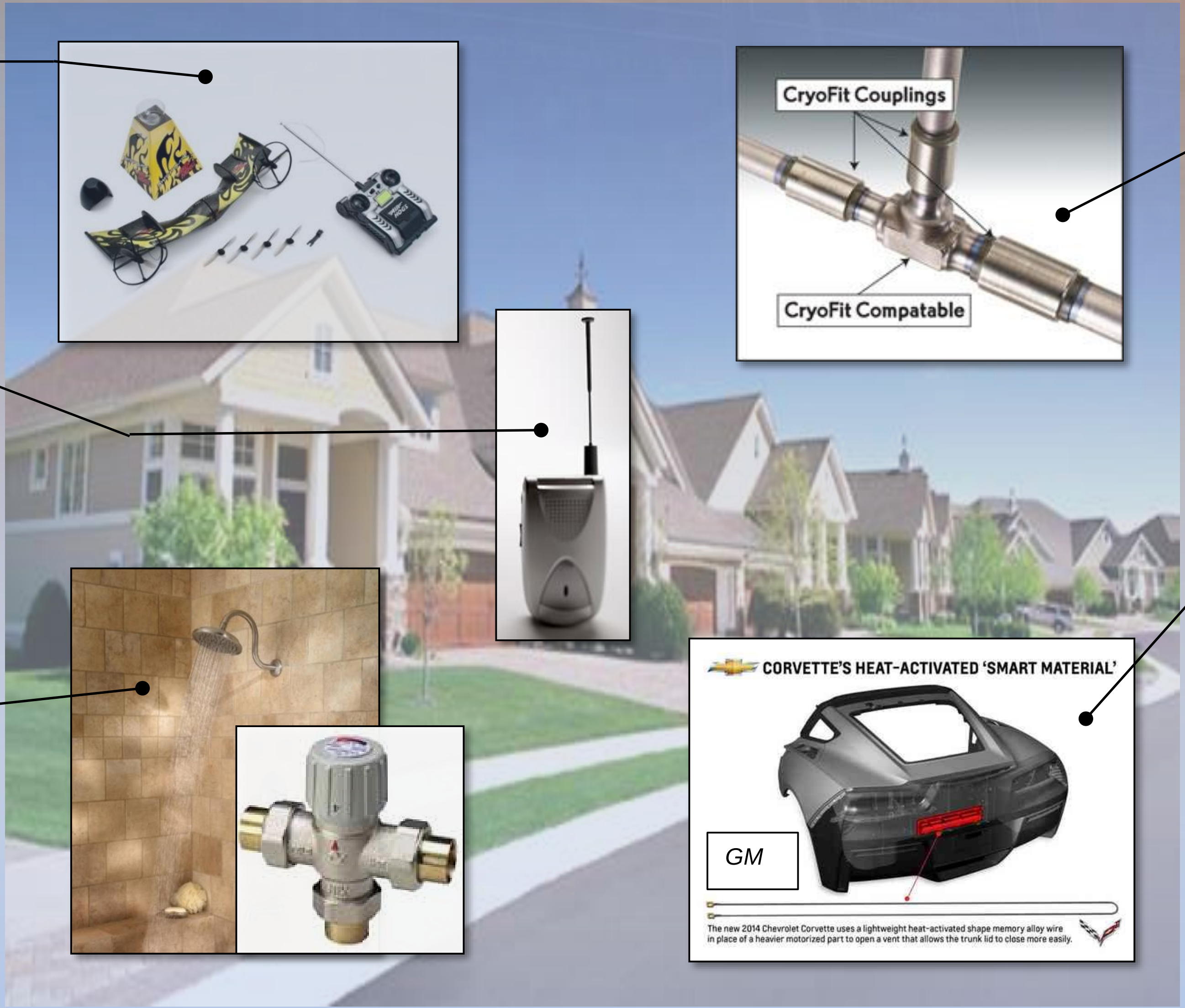
NiTi Bearings
- Corrosion resistant
- Non-galling properties
- High yield
- Provides drinking water to astronauts

Application of Shape Memory Alloys | *Consumer Goods*

Toys
- RC Helicopter
- Dolls
- Robots

Consumer Devices
- Antennas
- Electronics
- Computers
- Switches
- Latches

Valves
- Anti-scald (safety)
- Home appliances
- Air conditioners



Couplings
- Plumbing
- Mechanical
- Electrical

Automotive Industry
- Louvers
- Quiet actuators
- Door handles
- Fasteners
- Lumbar Supports

Application of Shape Memory Alloys | *Oil and Gas*

Deep-Water Platforms

- Deep-water shutoff valves
- Underwater connectors
- Self-torqueing fasteners
- Seals

Crude Extraction

- SmartRAM™ actuators (*LMP*)
- SMA couplings

Down-hole Drilling

- Abrasion-resistant components
- Actuators
- Vibration damping

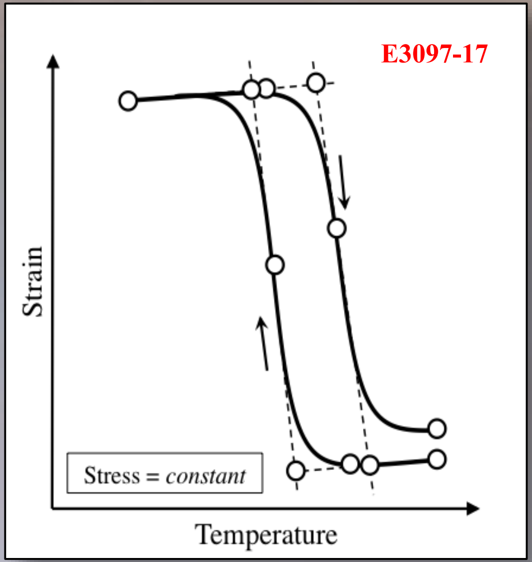
ASTM Standards

For biomedical and or superelastic

- F2004-05
- F2005-05
- F2063-05
- F2082-06
- F2516-07
- F2633-07

For SMA Actuation

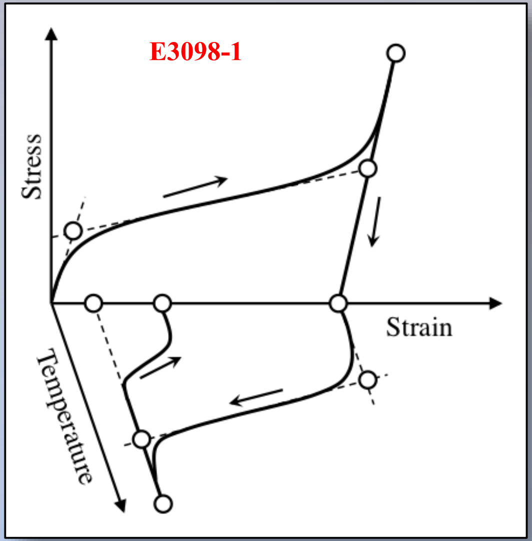
- E3097-17
- E3098-17



Standard Test Method for **U**niaxial **C**onstant **F**orce **T**hermal **C**ycling of Shape Memory Alloys (UCFTC)

Examples:

- Determine material properties
- Multi-cycle actuator



Standard Test Method for Uniaxial Pre-strain and Free Recovery of Shape Memory Alloys (UPFR)

Examples:

- Determine material properties
- One time actuation
- Release mechanism, deployment devices

Vendor material data sheets

- Dynalloy, Inc → http://www.dynalloy.com/
- Fort Wayne Metals → https://fwmetals.com/
- Johnson Matthey → http://jmmedical.com/
- SAES Group → https://www.saesgetters.com/products-functions/products
- TiNi aerospace → https://tiniaerospace.com/
- Ultimate R&D: → http://www.ultimateniti.com/
- Others…

Other Useful Resources

- CASMART—Consortium for the Advancement of Shape Memory Alloy Research and Technology
  http://casmart.tamu.edu/

- SMST—Shape Memory and Superelastic Technologies
  https://www.asminternational.org/web/smst/home?doAsUserId=vzMatAB%2FAxI%3D

- SMA journals https://www.springer.com/materials/characterization+&+evaluation/journal/40830

- SMA Conferences

  Materials and applications
  - https://www.asminternational.org/web/smst2017
  - https://www.asme.org/events/smasis
  - https://htsmas2018.dgm.de/home/

  Material Science
  - https://icomat2017.northwestern.edu/
  - http://www.lem3.univ-lorraine.fr/ESOMAT2018/

27) Benafan, O., Brown, J., Calkins, F.T., Kumar, P., Stebner, A.P., Turner, T.L., Vaidyanathan, R., Webster, J., Young, M.L.: Shape memory alloy actuator design: CASMART collaborative best practices and case studies. International Journal of Mechanics and Materials in Design 10, 1–42 (2013)

28) Wheeler RW, et al. Engineering Design Tools for Shape Memory Alloy Actuators: CASMART Collaborative Best Practices and Case Studies. ASME. Smart Materials, Adaptive Structures and Intelligent Systems, *Volume 1: Multifunctional Materials; Mechanics and Behavior of Active Materials; Integrated System Design and Implementation; Structural Health Monitoring* doi:10.1115/SMASIS2016-9183.

The Power of SMAs—Seeing is Believing

(Group exercise)

1. Subjects covered: Electrical heating; relationship of resistance to heating rate; heat versus temperature; how current divides, when given alternative paths; relationship of voltage to heating rate; relationship of transition temperatures to bias or return forces; leverage; moment arms; battery voltages; elasticity; spring dynamics; and more.

2. Sets of 3 diameter sizes wires, consisting of 2 different transition temperature wires for each wire size.

Ready to test your SMA knowledge?

(Group exercise)

1. Form team
2. Brainstorm to determine application for smart/adaptive structure
3. Determine requirements/define functions
4. Select methods to fulfill functions
5. Make sketch that shows configuration
6. Make sketch that shows interfaces
7. Present concept

Many thanks to contributions from:

CONSORTIUM FOR THE ADVANCEMENT OF SHAPE MEMORY ALLOY RESEARCH AND TECHNOLOGY
CASMART
Government Academia Industry

DYNALLOY, Inc.
Makers of Dynamic Alloys

FORT WAYNE METALS
Turning knowledge into solutions.

MIGA
MOTOR COMPANY
MODERN MOTION.

NASA GRC SMA Team

List of Symbols

Af	Austenite finish
As	Austenite start
DSC	Differential Scanning Calorimetry
EDM	Electrical Discharge Machining
GRC	Glenn Research Center
HTSMA	High Temperature Shape Memory Alloy
Md	Martensite desist
Mf	Martensite finish
Ms	Martensite start
NASA	National Aeronautics and Space Administration
SE	Superelasticity
SMA	Shape Memory Alloy
SME	Shape Memory Effect
TWSME	Two-Way Shape Memory Effect

Othmane Benafan, Ph.D. | *Course Instructor*

Othmane Benafan, Ph.D.

The instructor for this course is Dr. Othmane Benafan. Dr. Benafan is a materials research engineer in the High Temperature and Smart Alloys Branch at NASA Glenn Research Center. He received his Ph.D. in Mechanical Engineering from the University of Central Florida in 2012. Since joining NASA Glenn, his work entails developing novel shape memory alloys (SMAs) with high and sub-zero actuation temperatures to enable new, lighter weight aerospace mechanisms and shape-changing components for temperature ranges beyond the limits of commercial SMAs. His work is continuing to develop the alloys, address scale-up issues, assess durability, and develop specifications and standards, all of which are critical to enable the technology to be adopted for flight. Othmane is currently the Executive Chairman of the joint industry-government-academia Consortium for the Advancement of Shape Memory Alloy Research and Technology (CASMART), and the Vice President of the ASM International Organization on Shape Memory and Superelastic Technologies (SMST).

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Email:
othmane.benafan@nasa.gov