

# Utilizing Shape Memory Alloys for Novel, Non-Pneumatic Tire Design

*Designing for the Best of Both Worlds*



**Dr. Santo Padula II**

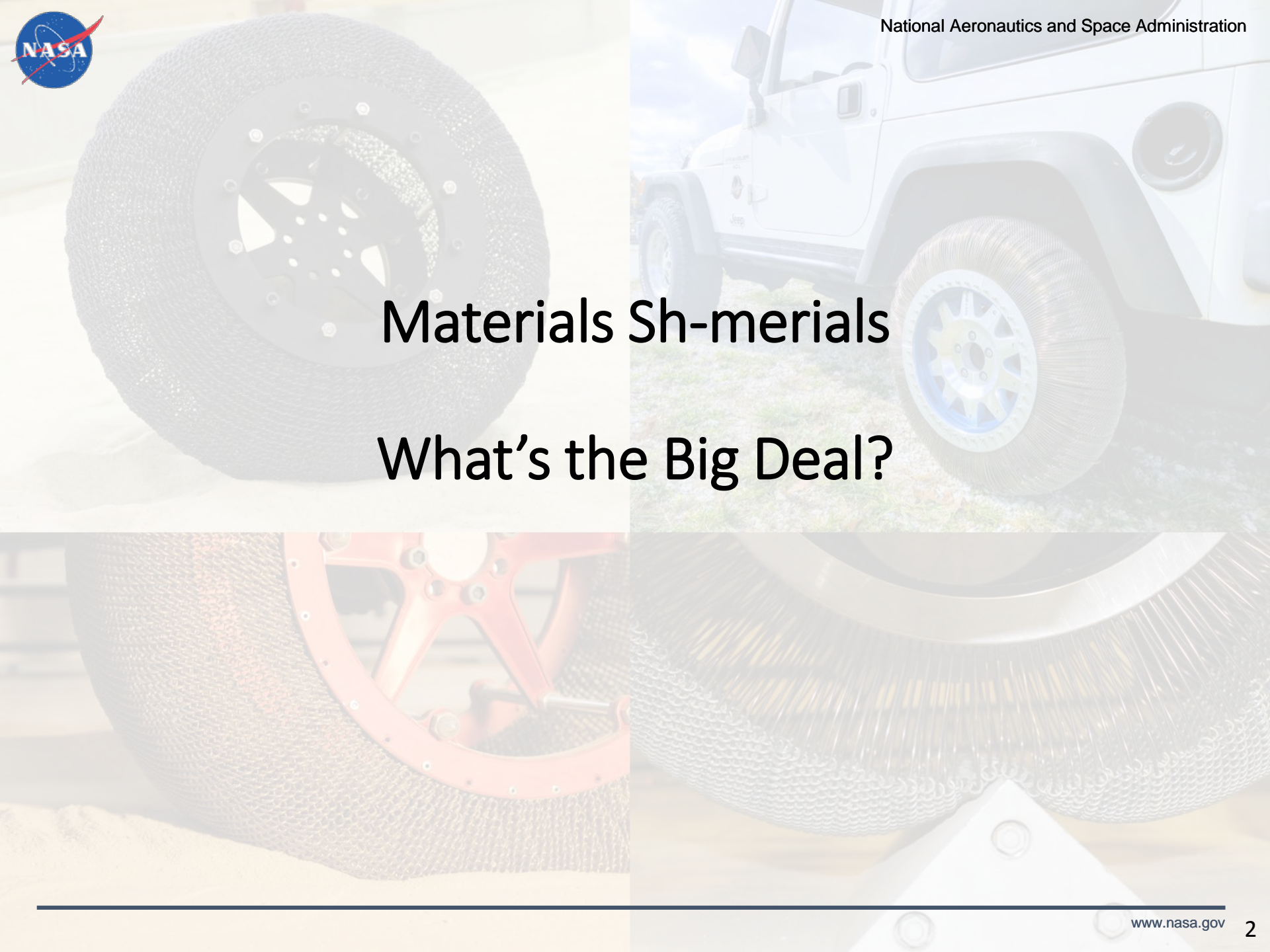
**NASA Glenn Research Center, Cleveland, OH**





# Materials Sh-merials

## What's the Big Deal?

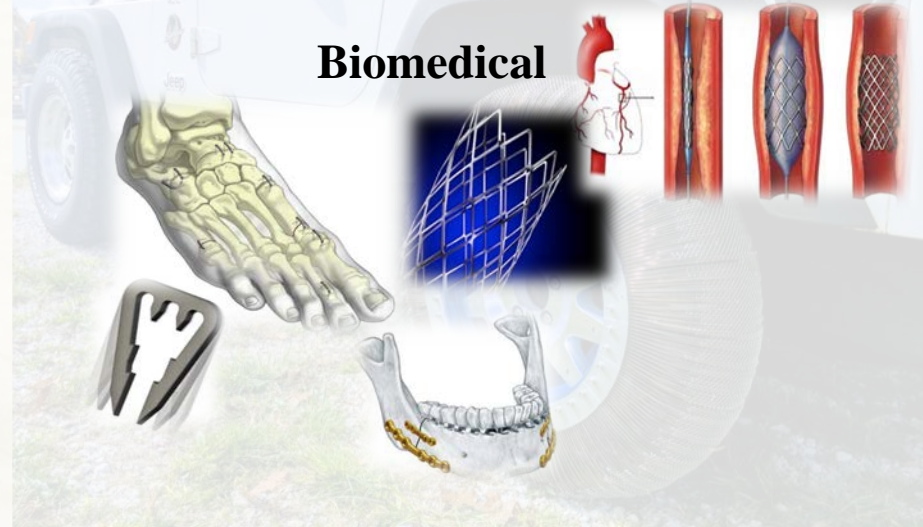




# Design of Products Requires Proper Material Choice



**Aerospace**



**Biomedical**



**New Innovative Products**



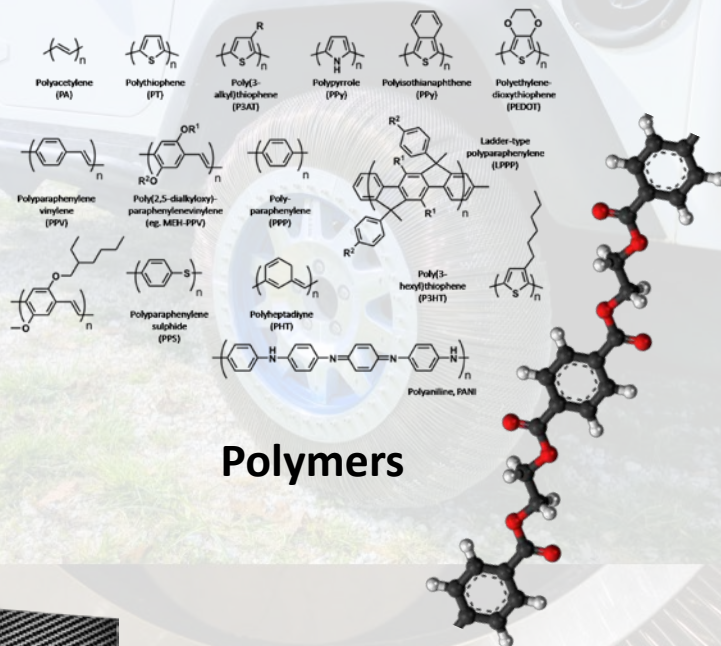
**Civil & Commercial**

# Various Types of Materials for Use

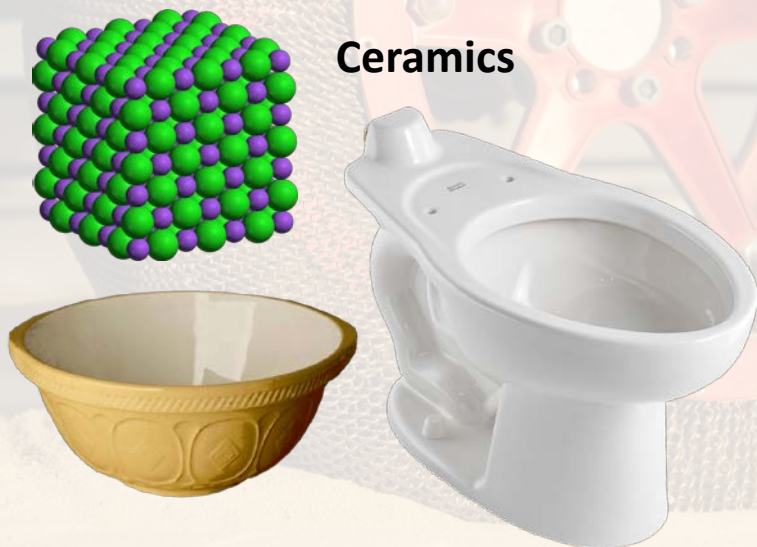
## Metals



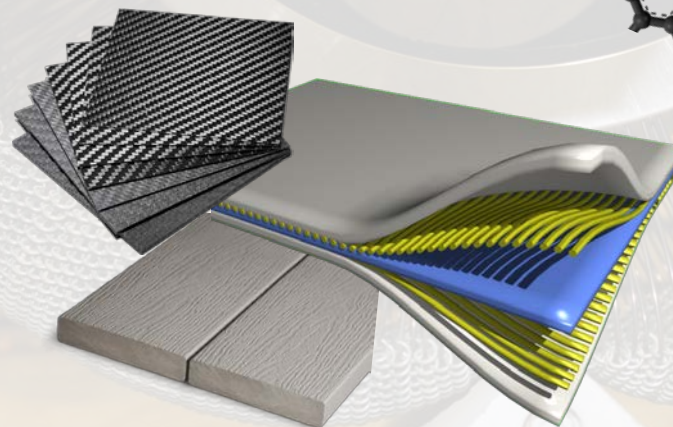
## Polymers



## Ceramics



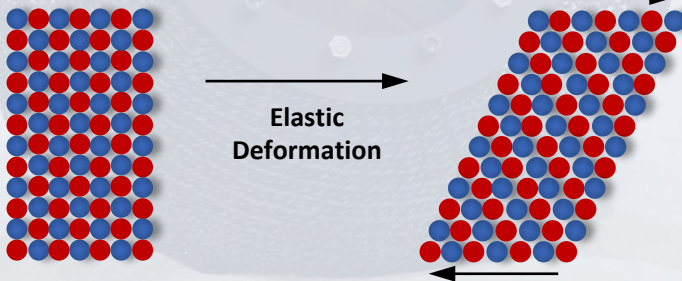
## Composites



# Conventional Metal Deformation

- ☐ Require imposed forces/stresses only generate **ELASTIC** deformation.

Undeformed Crystal

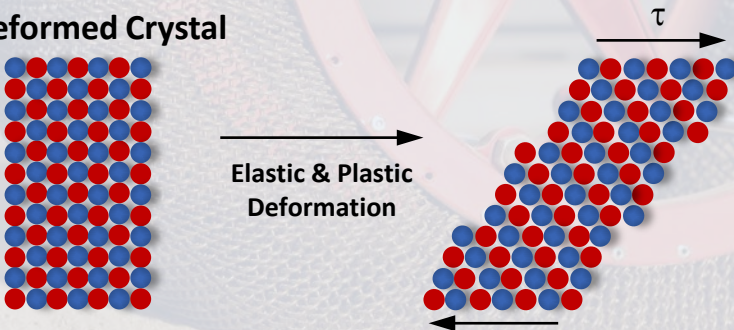


## **Elastic deformations**

- ✓ Distort the material lattice through bond stretch.
- ✓ Deformations are **REVERSIBLE**.

- ☐ If imposed forces/stresses create deformations that can't be accommodated by **ELASTIC** distortion of lattice – **PLASTIC** deformation (bond breakage).

Undeformed Crystal



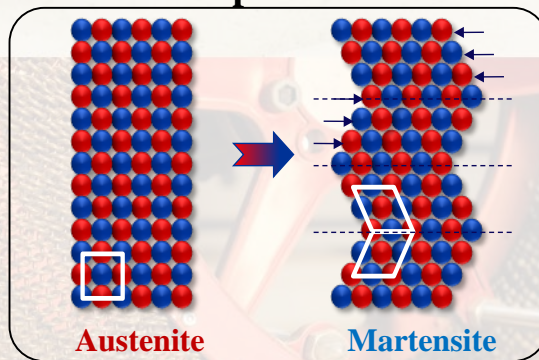
## **Inelastic deformations - Plasticity**

- ✓ Distort the material lattice through microstructural rearrangement (metallic materials - slip).
- ✓ Deformations are **IRREVERSIBLE**.
- ✓ Can only dissipate energy.

# Shape Memory Alloys: An Introduction

- ❑ Don't accommodate deformations through **ELASTIC** bond stretch.
- ❑ SMAs exhibit a **SOLID-TO-SOLID, REVERSIBLE PHASE TRANSFORMATION**.
- ❑ Transformation capable of storing **over 30x** the deformation that can be done in an **ELASTIC** bond stretch.

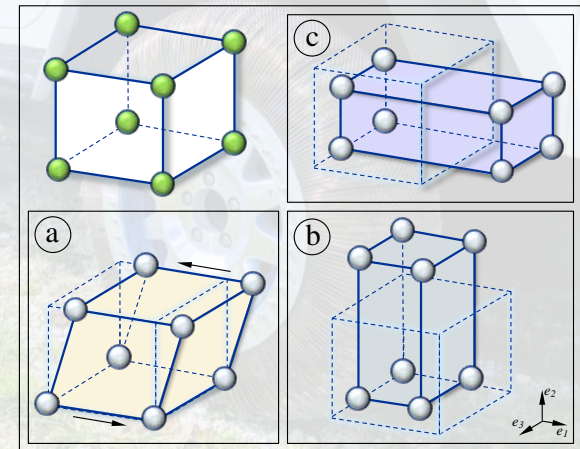
## Simplified 2D



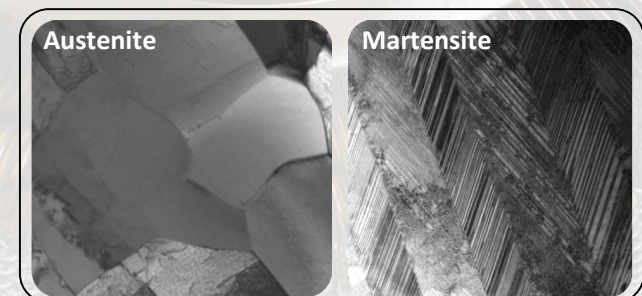
## ❑ How?

- ✓ Bain strain → (lattice deformation)
- ✓ Lattice invariant shear → (accommodation)
- ✓ **Inelastic** deformation (transient twinning) → **REVERSIBLE**

## Variant selection



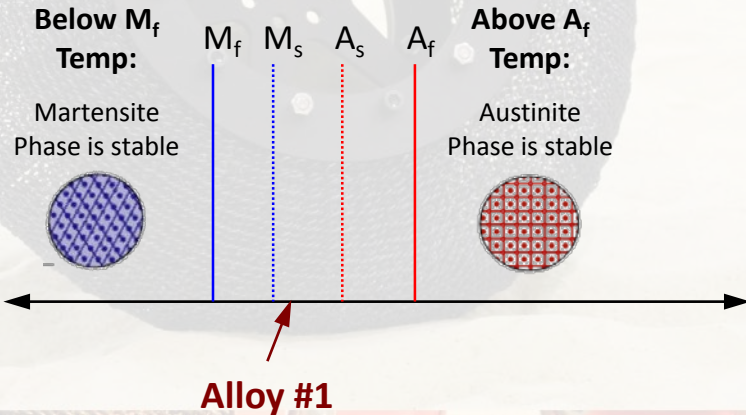
## Microstructure



Courtesy of A. Garg



# Alloy Chemistry and Thermomechanical Processing Alters Temperature at Which Phase Transformation Happens



**Pseudoelastic / Superelastic Behavior**

## Temperatures

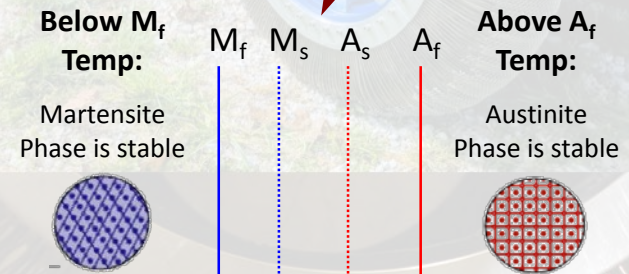
Martensite Finish:  $M_f$   
 Martensite Start:  $M_s$   
 Austenite Start:  $A_s$   
 Austenite Finish:  $A_f$

**Ambient Condition**

RT = 25 °C

**Actuator Behavior (SME)**

**Alloy #2**



**Solid-state Phase Transformation between two phases**

Temperature

**Allows us to tailor the transformation to suite the application requirements.**



# Shape Memory Alloys Thermally Induced Shape Recovery

**One-way Shape Memory Effect**



**Biased, One-way Shape Memory Effect  
(for Continuous Motion)**



**The thermally activated mode of SMA enables solid-state actuation mechanisms for a host of new and innovative applications**

# Practical Example of Difference between Conventional Material and Shape Memory Alloys

## Brass

*Plastic Buckling & Fracture*



## Stainless Steel

*Plastic Deformation*



## Shape Memory Alloy

*Reversible Pseudoelasticity*

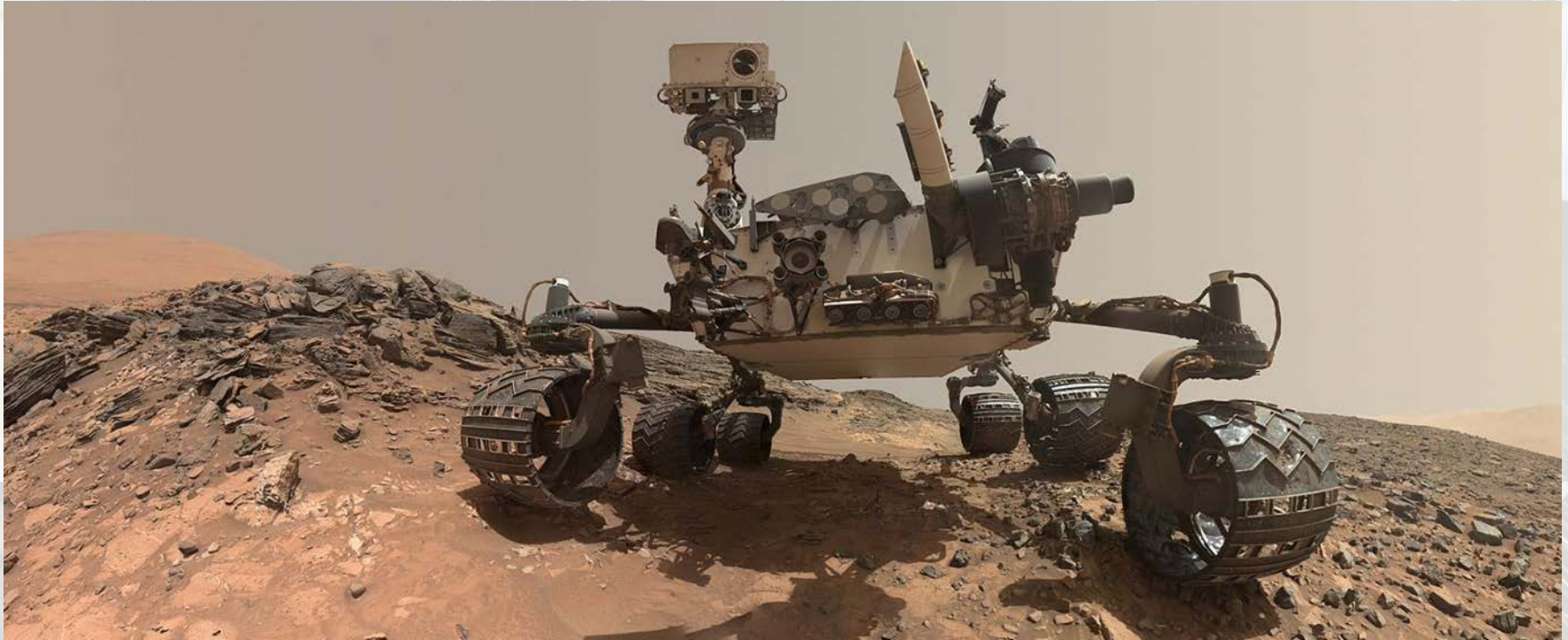


The reversible, solid-state phase transformation that occurs in Shape Memory Alloys (SMAs) is capable of storing **over 30x** the deformation that can be done in a material required to accommodate the deformation solely through **elastic** bond stretch.

**The mechanically induced mode of SMAs enables a  
paradigm shift in thinking and design**

# What's the Applicability of This to NASA?

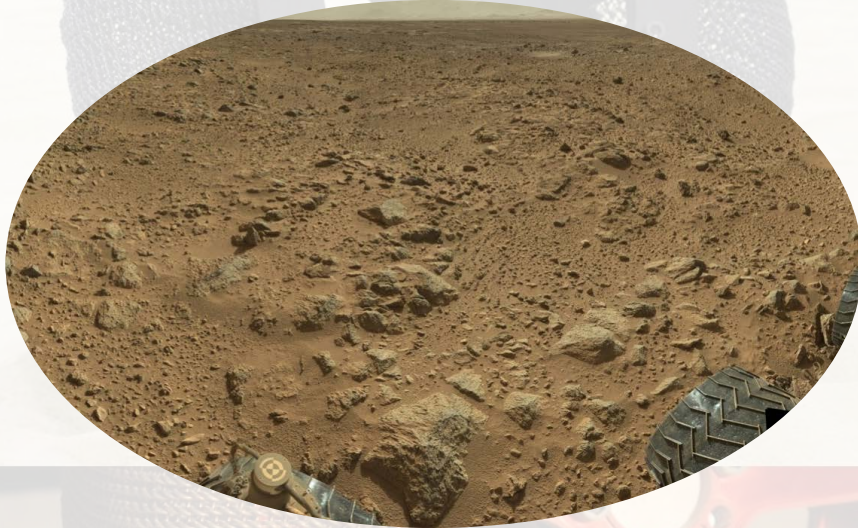
# Mars Curiosity Rover



In 2013, a little over a year after the Mars Curiosity Rover landed on Mars, engineers began to notice that the rover was experiencing significant wheel damage. This damage was attributed to the unexpectedly harsh regolith that was being encountered by the rover, causing concern about the ability of the rover to complete its intended mission.

# Current Rover Wheel Problem

Actual Terrain being encountered



Mars Curiosity Wheel

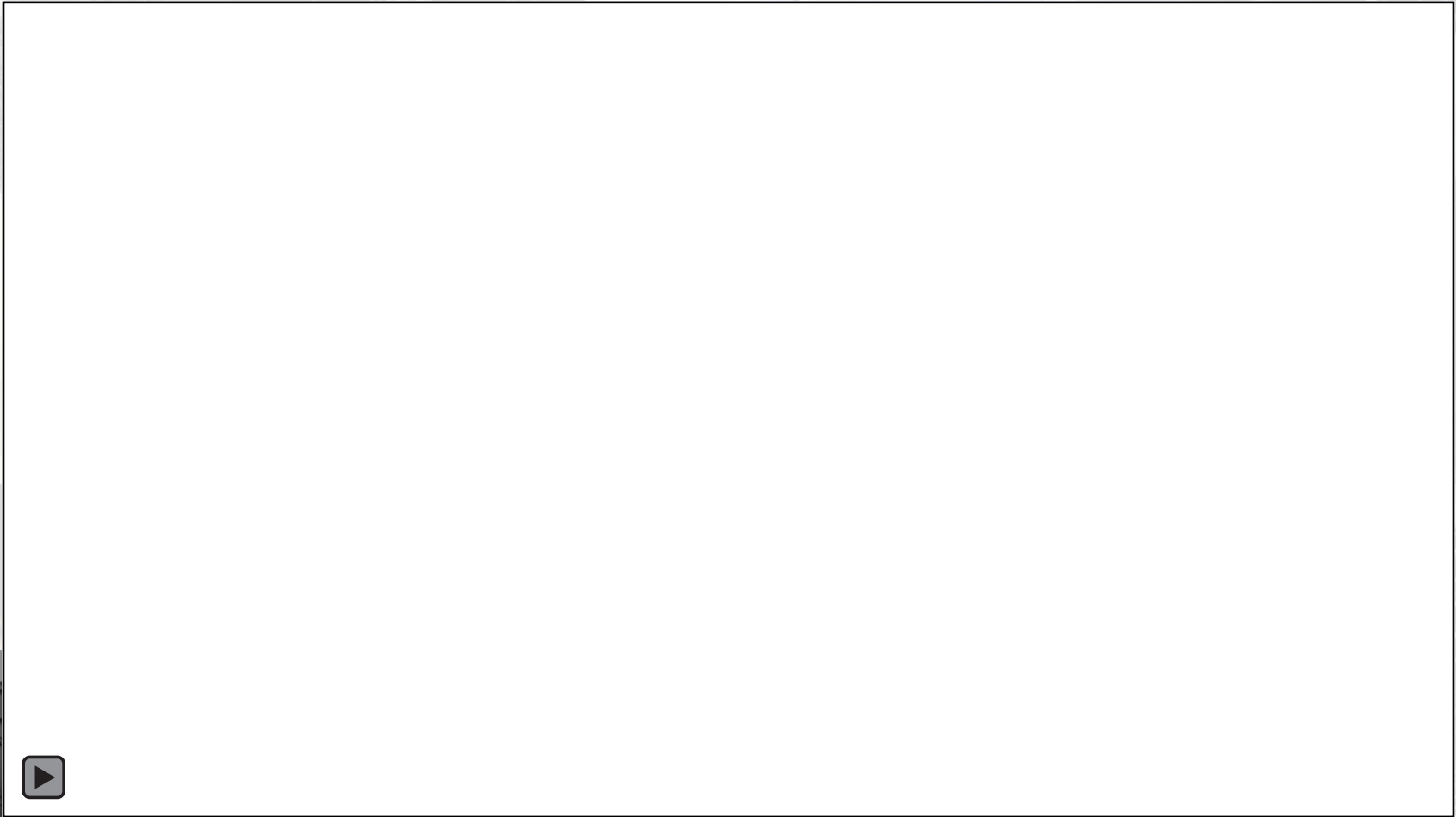


- ❑ Actual forces on wheels causing larger deformations than expected.
  - ✓ Can't be accommodated by **ELASTIC** deformation
  - ✓ Causing **PLASTICITY** and **FRACTURE**
- ❑ Leading to punctures of the structure and grouser failures.

***Desire to develop alternative capabilities that overcome the current limitations to improve mission capability and performance.***



# Curiosity Rover Wheel Acquiring Damage





# Issues with Using Pneumatics in Space

❑ Vulcanized rubber is susceptible to a number of challenges when exposed to space environment:

- Cold temperatures can lead to embrittlement
- Exposure to solar radiation can damage bonding

} *Both lead to cracking*

❑ Potential for puncture

- Rough terrain could produce puncture failure

*The above primary issues can lead to loss of pressure which can be **MISSION ENDING***

# GRC's Original Spring Tire Utilized Conventional Metals (Spring Steel)

## 2008: Lunar mobile habitat

- “Chariot”/“SEV” (NASA JSC)
- Nominal load = 550 lbf
- Excellent envelopment and traction
- Susceptible to permanent deformation at high loads



## 2013: Lunar excavating vehicle

- “Centaur 2” (NASA JSC)
- Nominal load = 600 lbf
- Tires mounted in pairs (“dualies”) to accommodate the load
- Excellent traction but susceptible to permanent deformation at high loads

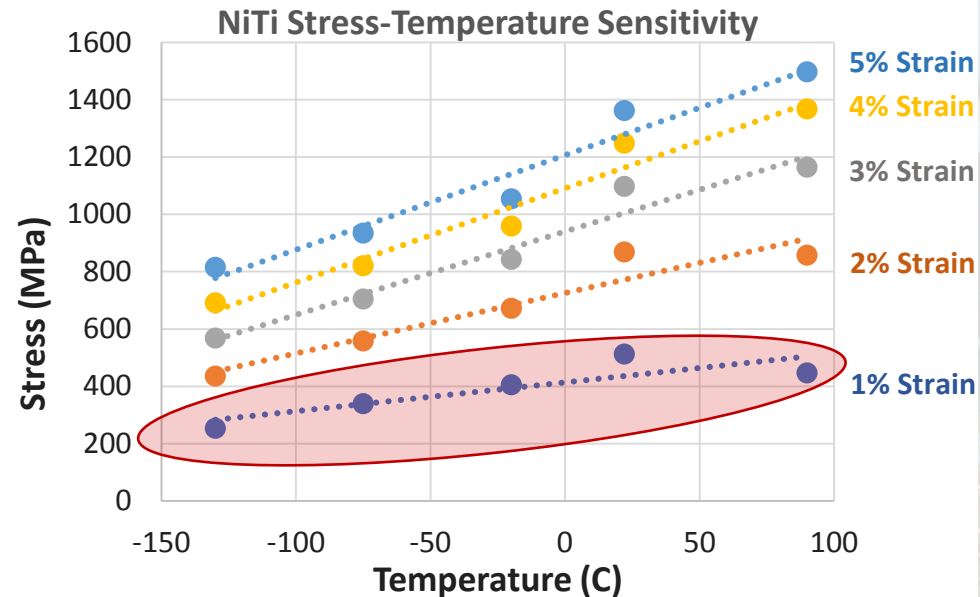
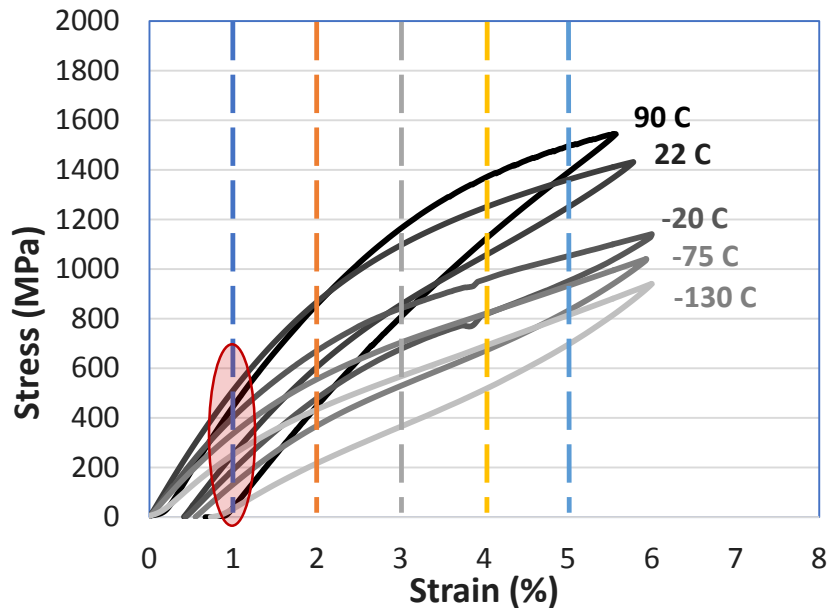


## 2016: Mars 2020 rover

- Designed with Mars 2020 requirements
- Nominal load = 165 lbf
- Improved traction and durability vs. Martian rigid wheels
- Permanent deformation on JPL Life-test track



# Material Properties Required for Martian Rover Applications



- With proper thermomechanical treatment of the material - extremely low stress-temperature sensitivity can be maintained.
- When coupled to proper spring tire design – maintain similar tire performance across entire temperature regime.
- Proper design ensures almost infinite life (transformation capability far from exhausted).

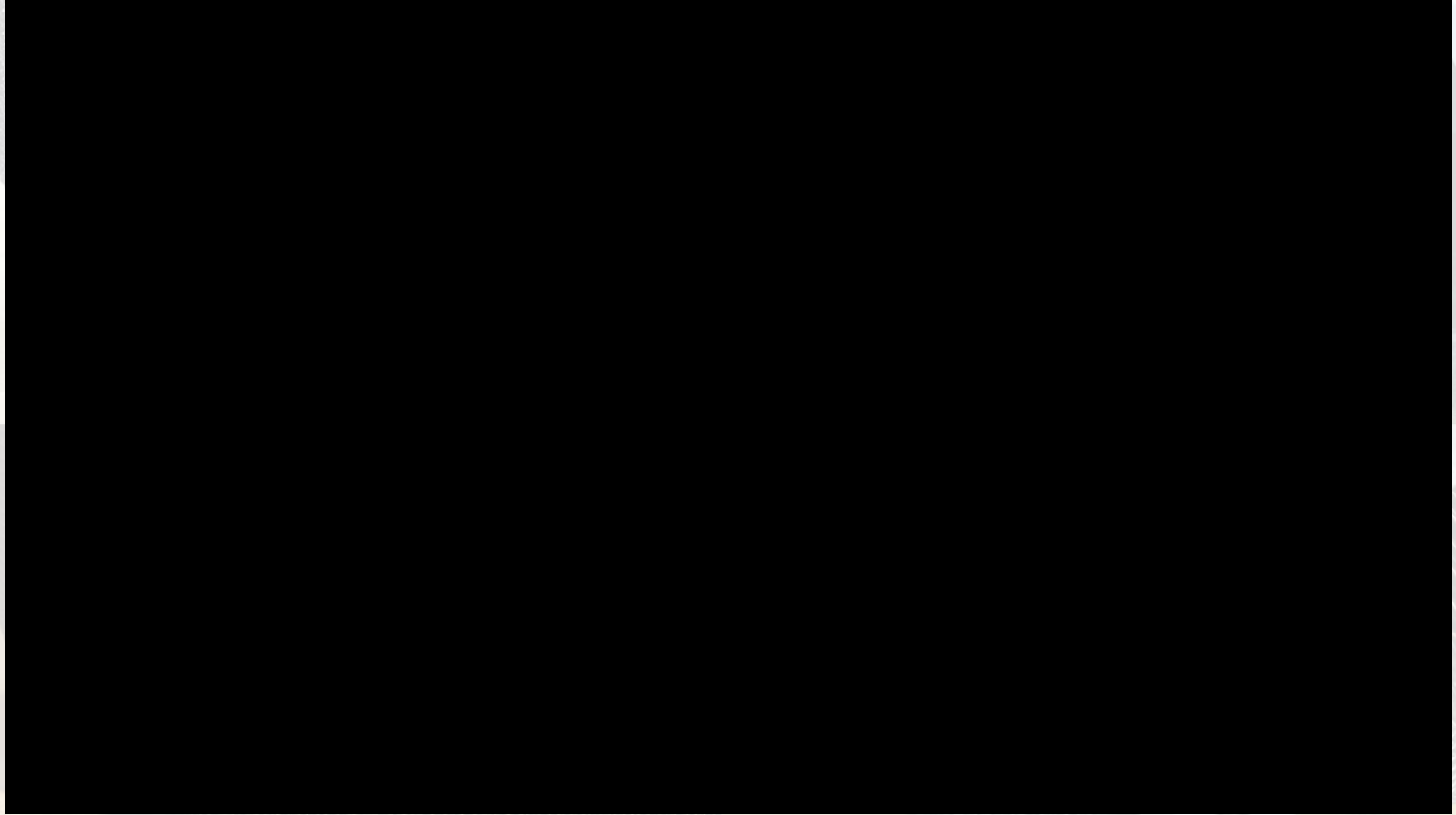
# Shape memory alloy (SMA) Spring Tire

- ❑ Utilization of **Nickel-titanium (NiTi)**, “*pseudoelastic*” shape memory alloy (SMA).
- ❑ Non-pneumatic, spring geometry construction.
- ❑ Compliant tire technology:
  - ✓ Carry significant load
  - ✓ Envelop obstacles without permanent deformation or damage
- ❑ Designed for specific Mars Temperature Requirements
  - ✓ Low Stress-Temperature Sensitivity
  - ✓ Capable of operating from -130 to +90 °C

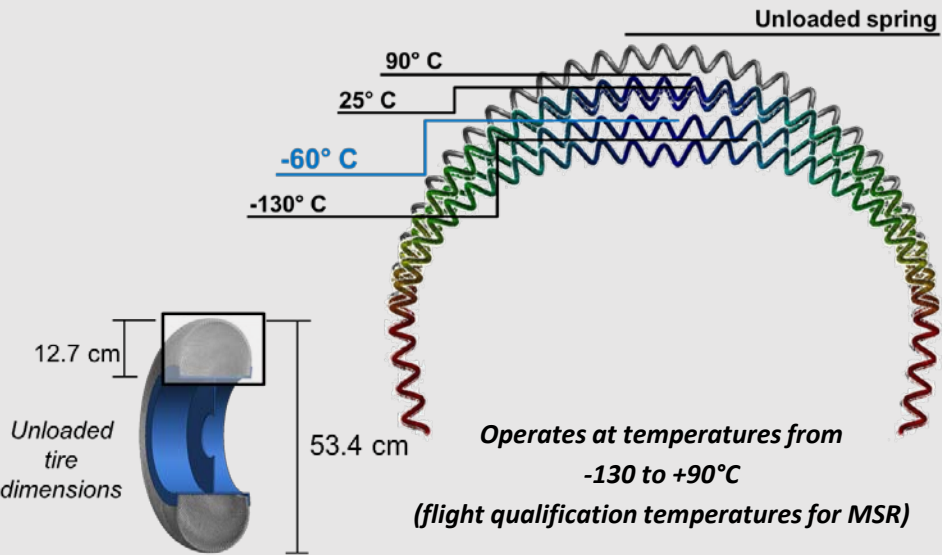




# Shape Memory Alloys in Action



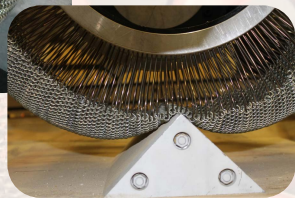
# Benefits of The Mars SMA Spring Tire



# Other Applications for Shape Memory Alloy Non-Pneumatic, Compliant Tires

- ❑ Later generations of SMA compliant tire utilize radial hoop geometries.
- ❑ Radial designs can carry much higher loads than coiled designs.
- ❑ More easily scalable for changes in load and tire size requirements for different applications.

Generation 2 – 500 lbf.



## ***Potential Applications Include:***

- ✓ Commercial Aircraft Tires
- ✓ Truck and Automotive Tires
- ✓ Military Applications
- ✓ Robotic Applications (Fire and Rescue)
- ✓ Off-road and Agricultural Vehicles

Generation 3 – 2000 lbf.



**Utilization of SMA in non-pneumatic tire designs is going to open a world of possibilities for the future of *Space* and *Terrestrial* applications.**



# Automotive Application Demonstrated

Generation 2  
2200 N (~500 lbf.)



Generation 3  
8900 N (~2000 lbf.)



**Generation 3 of the Shape Memory Alloy (SMA), Radially-Stiffened Tire Supported a Nominal Design Load of >2000 lbs. @ 2 inches of deflection**



# Questions?

