Ni-Ti Alloys for Tribological Applications: The Effects of Serendipity on R&D

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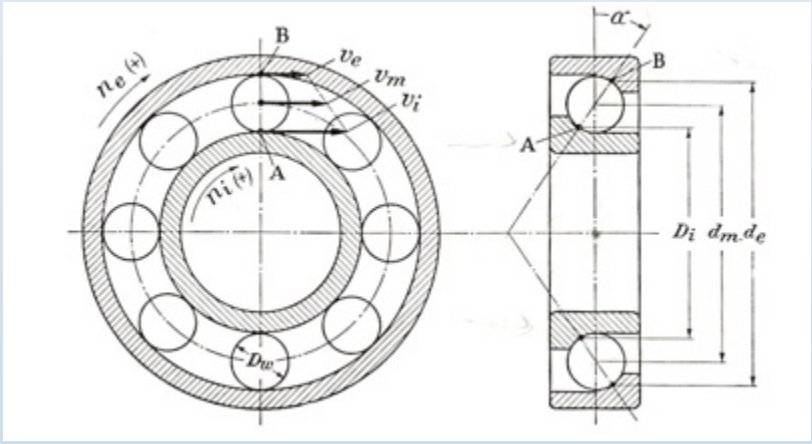
Bearings 101: The what, where, whys and hows

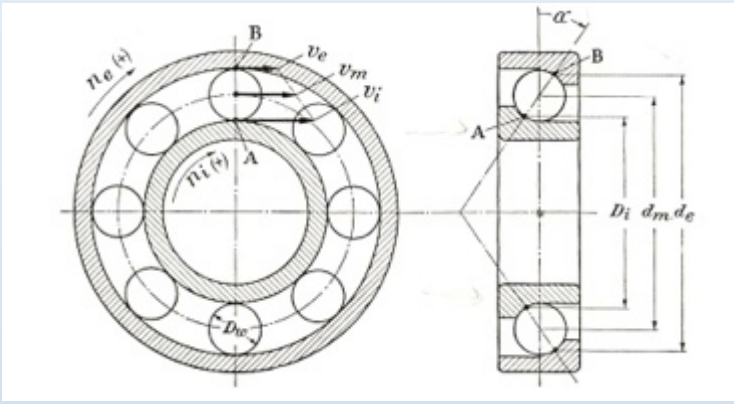
- **Definition: A bearing is a device that allows free movement between two connected machine parts.**
  - **Allows one part to turn while the other remains stationary (e.g. wheel vs. car frame, propeller vs. airplane wing).**
  - **Must operate with low friction and no wear.**
  - **Be able to withstand severe loads.**
  - **Ubiquitous (cars, planes, washing machines, spacecraft, pumps, fans, computer disk drives, roller skates and bicycles).**
- **Commonly rely on balls rolling between tracks (races).**
- **Bearing materials must be hard.**



Materials Requirements: NASA sets the bar high

(Space challenges conventional technology)

- **Attributes sought:**
  - Hard (Rockwell C58 or better)
  - Wear-resistant and compatible with existing lubricants
  - Resistant to rolling contact fatigue (RCF)
  - Fracture resistant
  - Corrosion resistant (preferably immune)
  - Low density (to reduce centrifugal loads at high rpm)
  - Capable of producing ultra-smooth surface finishes
  - Dimensionally stable and easy to manufacture



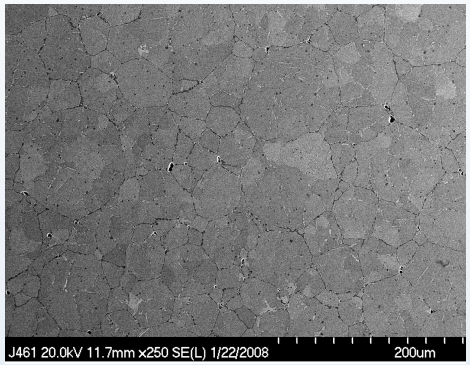
Bearing Material: State-of-the-Art (SOA)
(Current suite of candidates is severely limited)

- Four general types of bearing materials:
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si_3N_4 balls + steel races, a.k.a., hybrid bearings)
  - Superalloys (e.g., jet turbine blade alloys)
  - Non-ferrous alloys (bronze, nylon etc.)
- Each of these has inherent shortcomings:
  - Hard steels are prone to rusting (even “stainless steels” like 440C)
  - Superalloys and austenitic stainless steels (304ss) are soft.
  - Ceramics have thermal expansion mismatch and dent steel races
  - Non-Ferrous materials are weak and lack temperature capabilities
- No known bearing material blends all the desired attributes:
  - High hardness, corrosion immunity, toughness, surface finish, electrical conductivity, non-magnetic, manufacturability, etc.

New approach: 60NiTi-Superelastic

(Hard but resilient material based upon shape memory alloys)

- 60NiTi Basics: market name NiTiNOL 60
  - Invented by W.J. Buehler (late 1950's) at the Naval Ordinance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordinance Lab).
  - Contains 60 wt% Nickel and 40 wt% Titanium
  - 60NiTi is not a metal or a ceramic: a weakly ordered inter-metallic compound.
  - A close cousin to the shape memory alloy, NiTiNOL 55, but 60NiTi is dimensionally stable.
  - 60NiTi is bearing hard (Rockwell C60) but only half as stiff as steel.
  - Buehler found 60NiTi too difficult to manufacture but modern (ceramic) processing methods enable 60NiTi bearings with remarkable properties.



60NiTi microstructure

Highly polished 60NiTi bearing balls

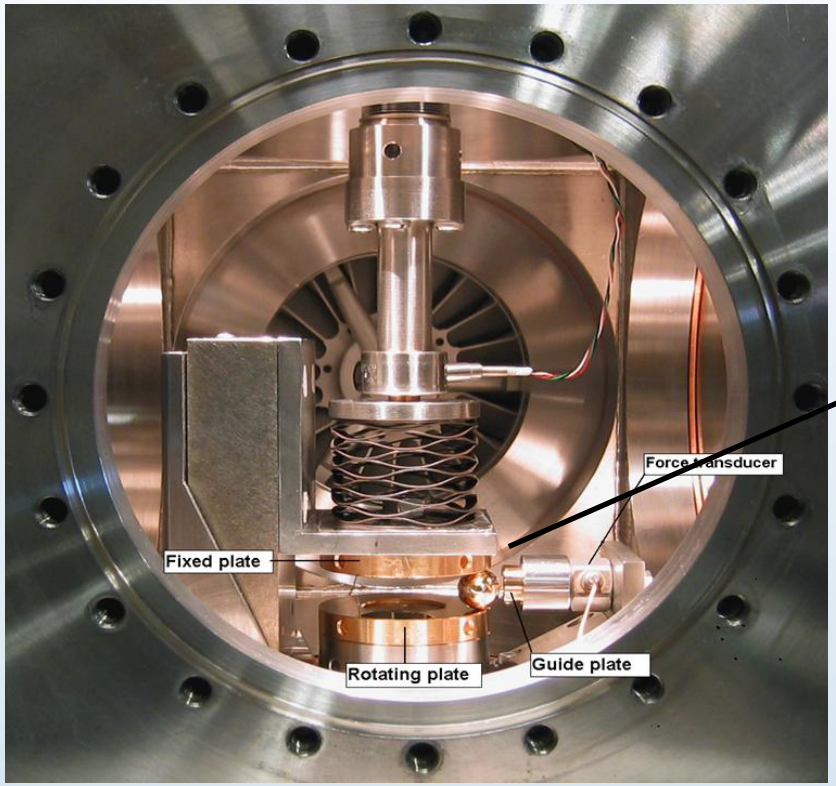
Nitinol 60: My story began with reluctance

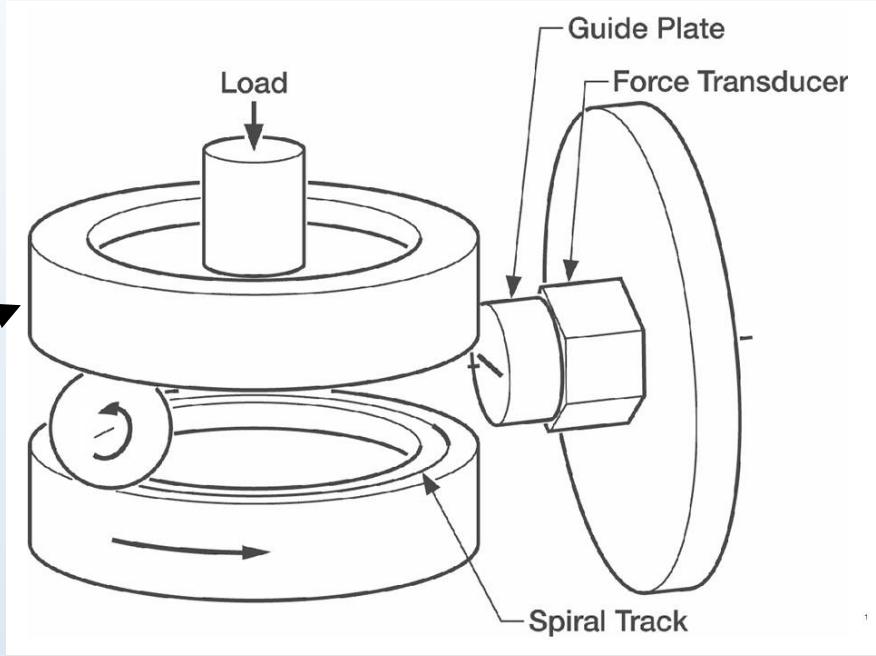
- What all tribologists know to be true:
  - Hard materials are stiff
  - Metals containing high amounts of Ti cannot be lubricated
  - Commercialization of new materials takes decades
- What NASA tribologists know:
  - Many missions have failed because designers used titanium alloys in moving mechanisms (gearboxes, deployment mechanisms, etc.)
  - NASA does not endorse products nor allow product testing.
  - The “cachet” and “status” of working with NASA can be alluring
  - Claims made by industry for new materials are typically exaggerated
- How NASA normally responds to requests for testing:
  - Polite listening, explanation of NASA engagement rules
  - Referral of requestor to industrial and academic test labs

Nitinol 60: Mixed with skepticism

- August 2004: first contact
  - Began with a ringing phone.
  - Glenn Glennon (Abbott Ball Co.) wanted to visit while in town to discuss having NASA do some testing of a new ball material, Nitinol 60.
  - Arranged a courtesy visit to meet with our customers (taxpayers).
- First Face-to-Face (F2F):
  - Abbott revealed “mystery material” composition, 60Ni/40Ti wt%
  - Politely explained NASA’s stance on endorsement
  - Surprised by combination of high hardness and low elastic modulus
  - Recognized unique properties (hard, corrosion immune)
  - I was intrigued and offered to run a few tribotests
- Manufacturing challenge:
  - Material quality was very low
  - Two years invested in guiding Abbott through powder metal process

Tribology Evaluation: Spiral Orbit Tribometer (SOT)
(Run with skepticism, Ti is a poor tribomaterial)

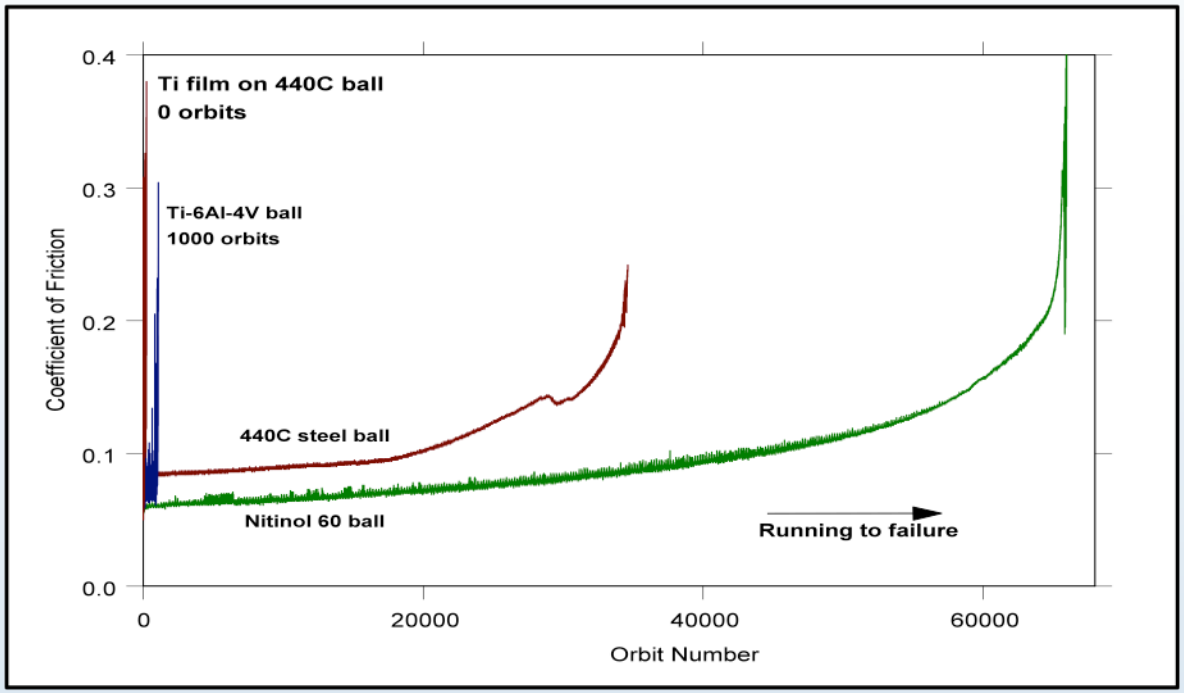




Specimen configuration

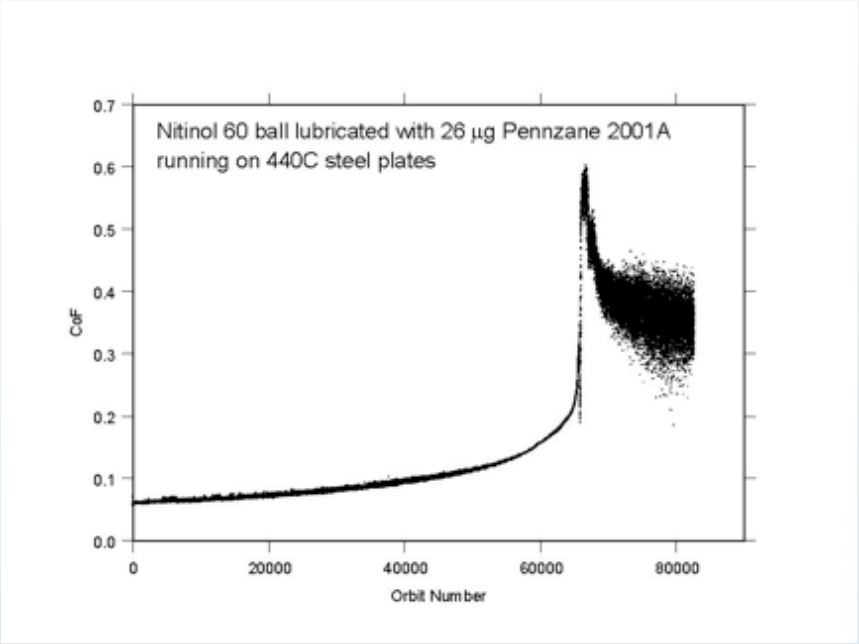
SOT is a rolling tribology test with minimal lubricant that experiences a slight scrub against guide plate once per revolution. SOT mimics instrument ball bearings very well and is used to evaluate materials and lubricants. Tests typically run in vacuum to simulate space environment under boundary lubrication.

60NiTi: Surprisingly good tribo-behavior

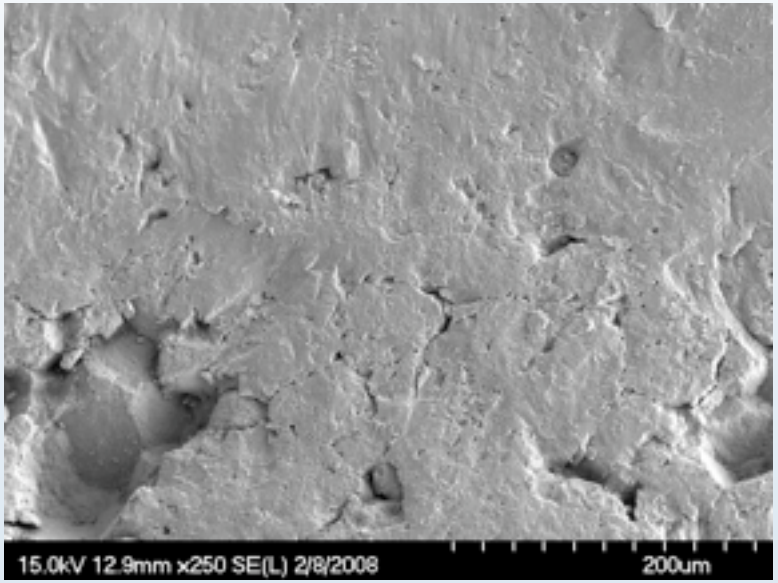


- Test confirms that that pure titanium and conventional alloys (Ti-6Al-4V) are poor tribological materials.
- 60NiTi exhibits lower running friction than 440C stainless steel.
- 60NiTi yields consistently longer lubricant life than 440C.

NiTi 60: Behavior after lubricant is gone



One test was run long after lube was consumed.



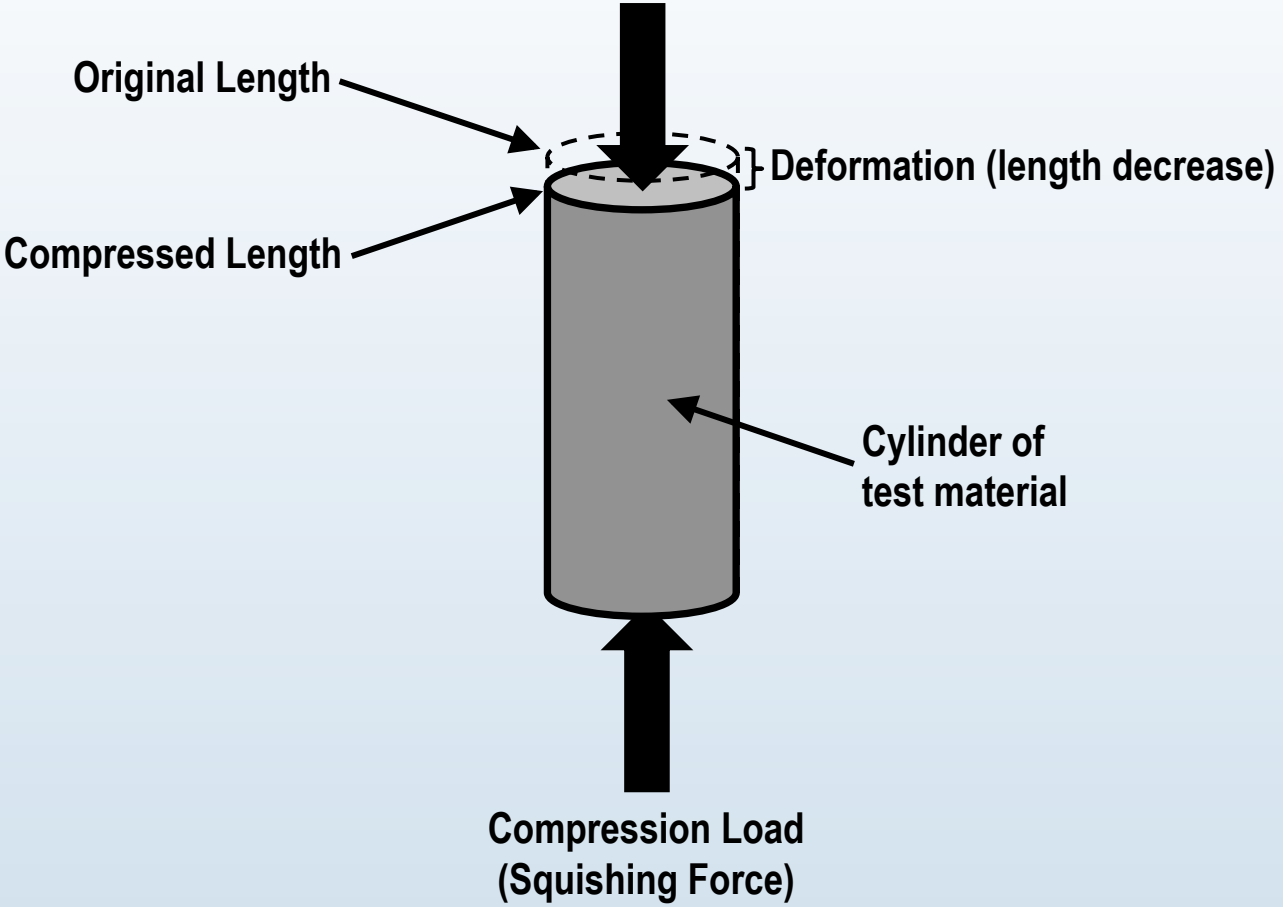
"Dry" operation yielded mild abrasive behavior with moderate friction.

- 60NiTi tribology is good. Even when lube is depleted galling isn't observed.
- What about 60NiTi's other properties relevant to bearings?

Nitinol 60: Becoming a believer

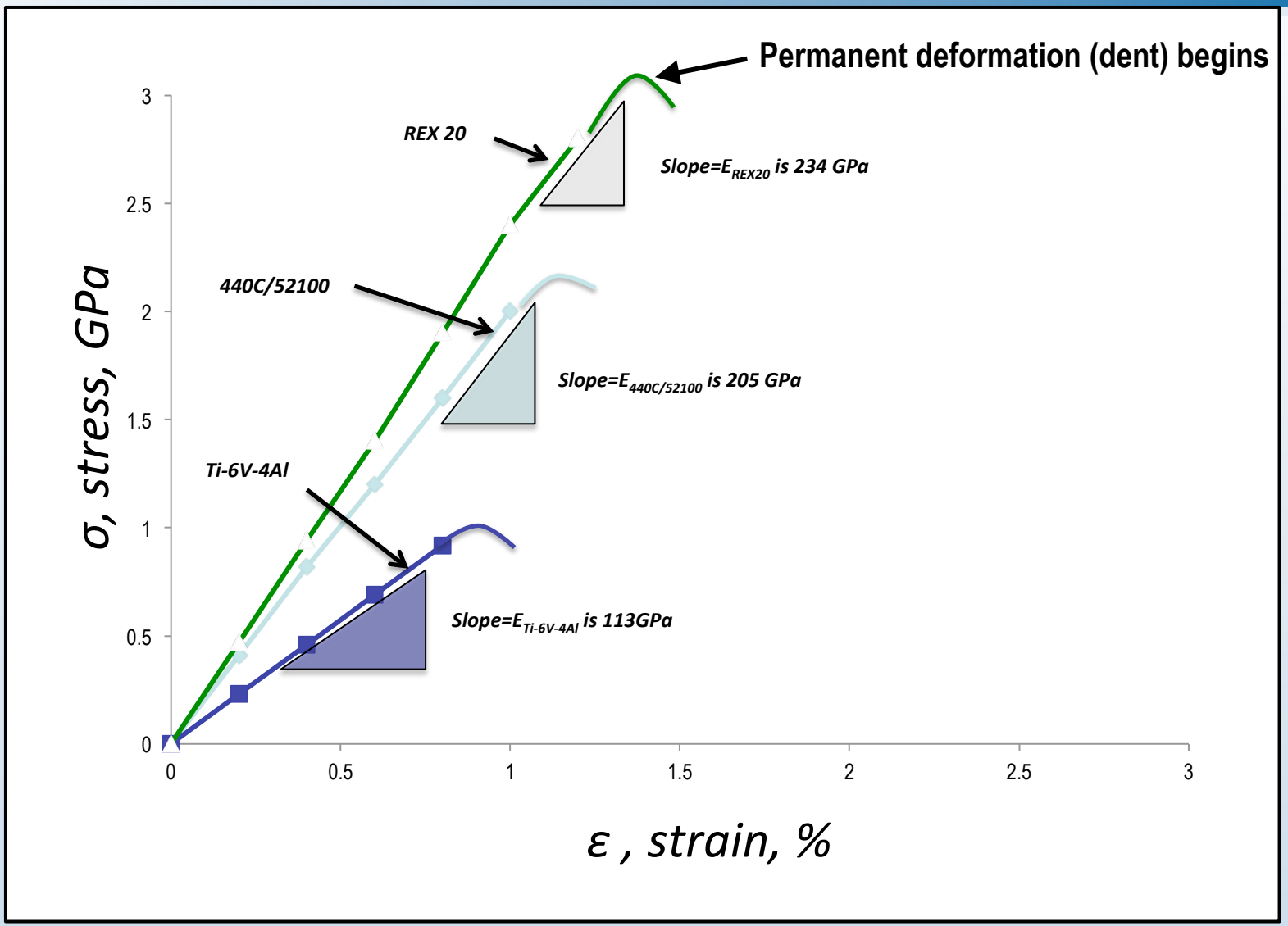
- NASA Infrastructure: Shape memory alloy
  - Decades of NiTi shape memory alloy development “kick-started” investigation into the ni-rich alloys.
  - Explored the effects of Ni:Ti ratio on hardness.
  - Measured typical properties (stress-strain) and made startling observation.
  - Despite its high hardness, 60NiTi is highly elastic.
- NiTi alloy potential:
  - Could the unique combination (hard yet superelastic) yield new benefits?
  - Could the NiTi materials system be the basis for new applications?

Conventional Metals: Elastic Behavior



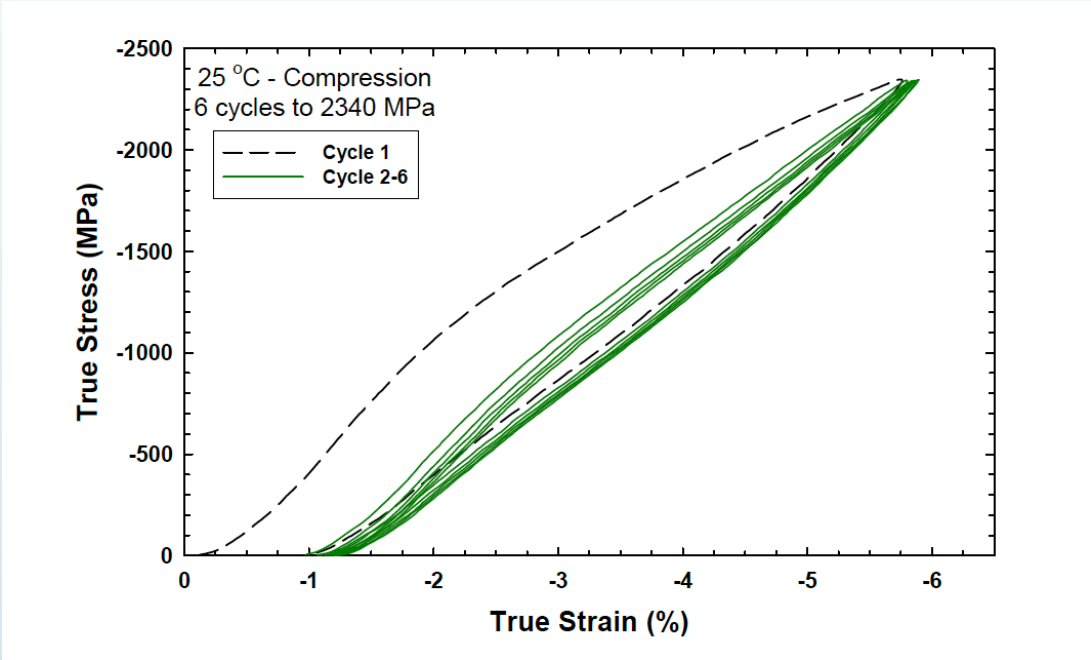
- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.

Conventional Metals: Elastic Behavior



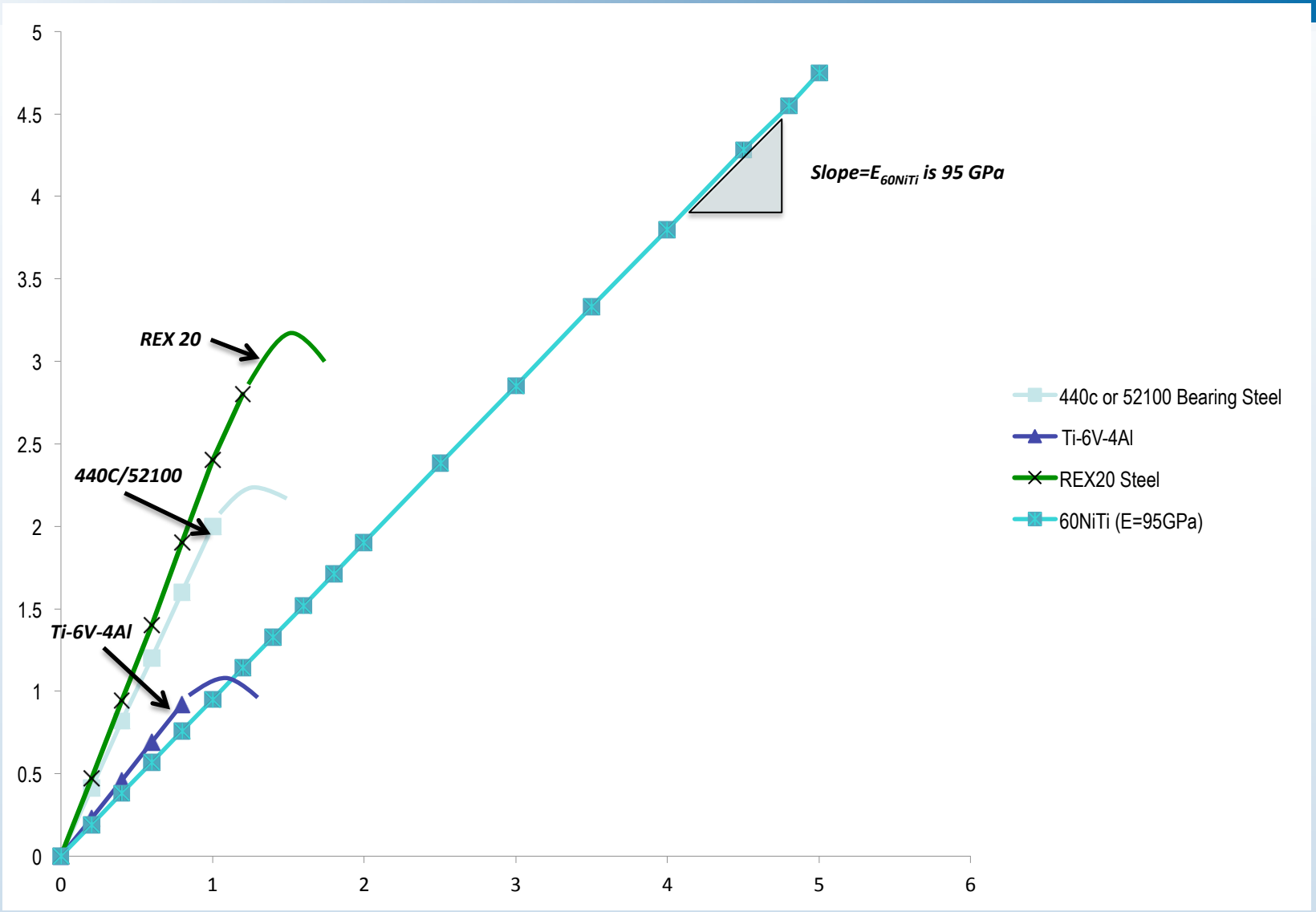
Material Testing:
(60NiTi-Compressive behavior)

- **Compressive behavior**
  - **Enormous recoverable strain (vs. ~1% or less for hardened steels)**



Highly Elastic Behavior

60NiTi: Stress-Strain Behavior



Technical Properties Comparison:

Property	60NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56 to 62 HRC	58 to 62 HRC	1300 to 1500 Hv	60 to 65 HRC
Thermal conductivity W/m-°K	~9 to 14	24	33	~36
Thermal expansion	~11.2×10^{-6}/°C	10×10^{-6}/°C	2.6×10^{-6}/°C	~11×10^{-6}/°C
Magnetic	Non	Magnetic	Non	Magnetic
Corrosion resistance	Excellent (Aqueous and acidic)	Marginal	Excellent	Poor
Tensile/(Flexural strength)	~1000(1500) MPa	1900 MPa	(600 to 1200) MPa	2500 MPa
Young's Modulus	~95 GPa	200 GPa	310 GPa	210 GPa
Poisson's ratio	~0.34	0.3	0.27	0.30
Fracture toughness	~20 MPa/√m	22 MPa/√m	5 to 7 MPa/√m	20 to 23 MPa/√m
Maximum use temp	~400 °C	~400 °C	~1100 °C	~400 °C
Electrical resistivity	~1.04×10^{-6} Ω-m	~0.60×10^{-6} Ω-m	Insulator	~0.18×10^{-6} Ω-m

- ***Primary Points***
  - ***Modulus is ½ that of steel, yet hardness is comparable.***
  - ***Tensile strength akin to ceramics.***

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  - Measured typical properties (stress-strain) and made startling observation.
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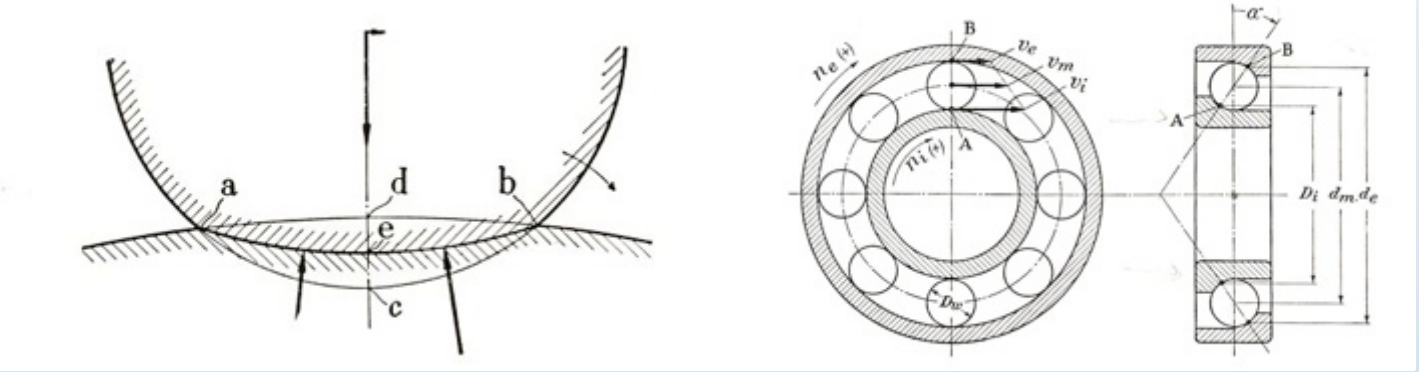
- **NiTi alloy potential:**
  - **Could the unique combination (hard yet superelastic) yield new benefits?**
  - **Does the ability to absorb deformation energy (resilience) translate into "game changing" increases in load capability?**
  - **Could the NiTi materials system be the basis for new applications?**

Low Modulus + Hard: A Technical Opportunity

- **Surprising and relevant behavior:**
  - **It is contrary to a century of experience with hard bearing materials!**
  - **Hard bearing materials are stiff and unforgiving and yield after small deformations.**
  - **Small contact points result in high stress and damage even under modest loads.**
  - **Brinell denting test can quantify resilience effect.**



Balls touch races at small points causing race surface dents

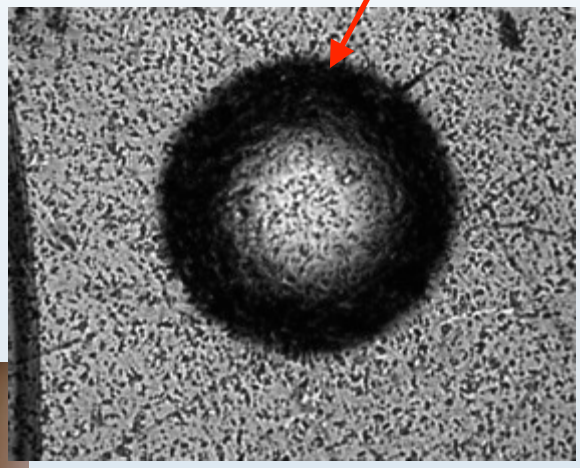
Dents on race surface cause rough running and premature failure

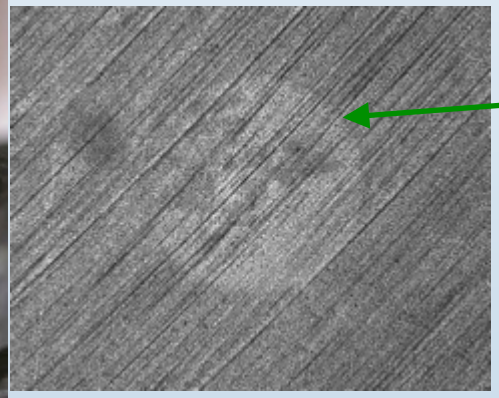
Resilience: Can 60NiTi withstand high dent loads?

(Static denting behavior)

- 60NiTi dent resistance
  - Threshold load to damage
  - Critical to launch vehicles and aircraft

Deep Brinell dent.



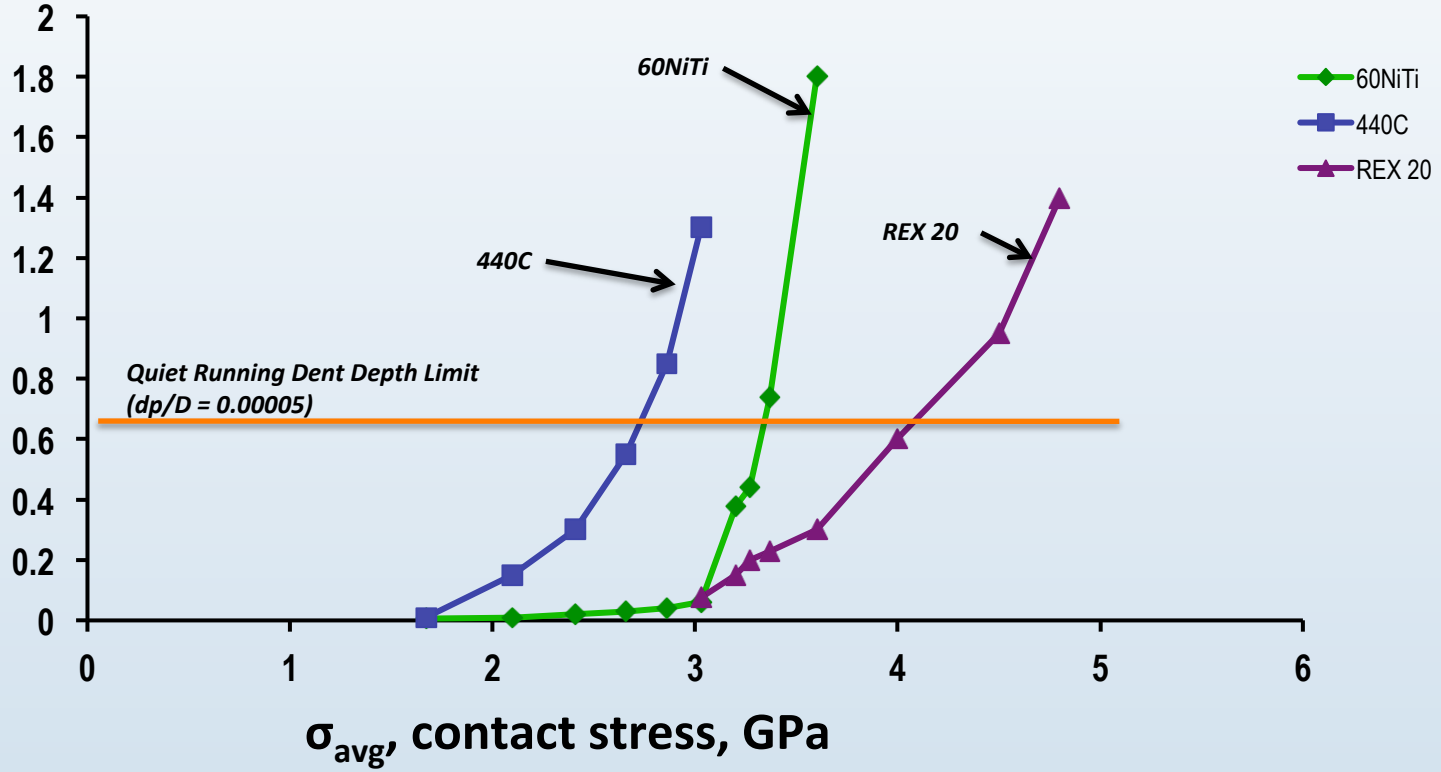


Threshold load visible dent.

Dent Depth vs. Hertz Contact Stress

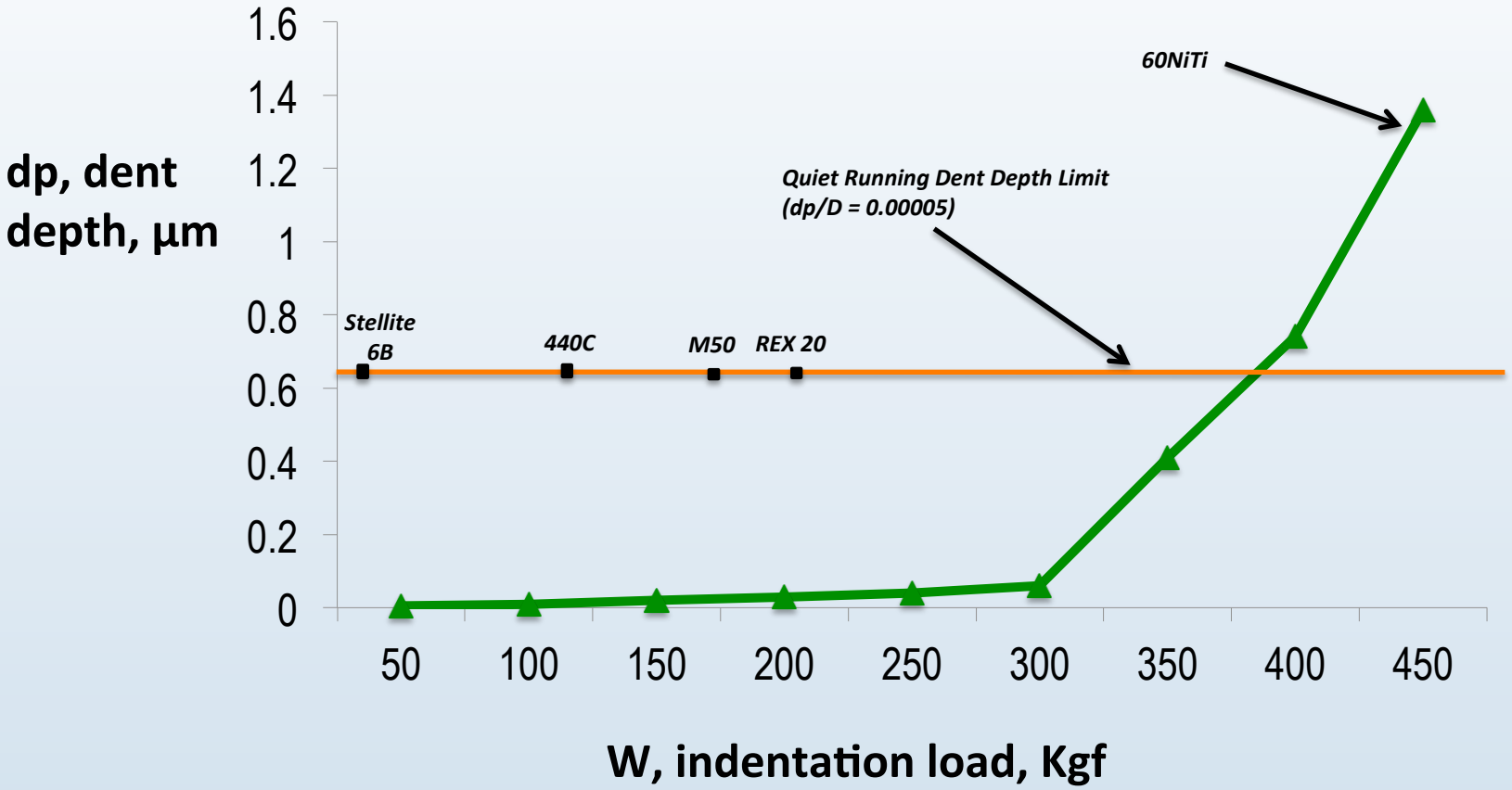
(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)

dp, dent depth, µm



Dent Depth vs. Load

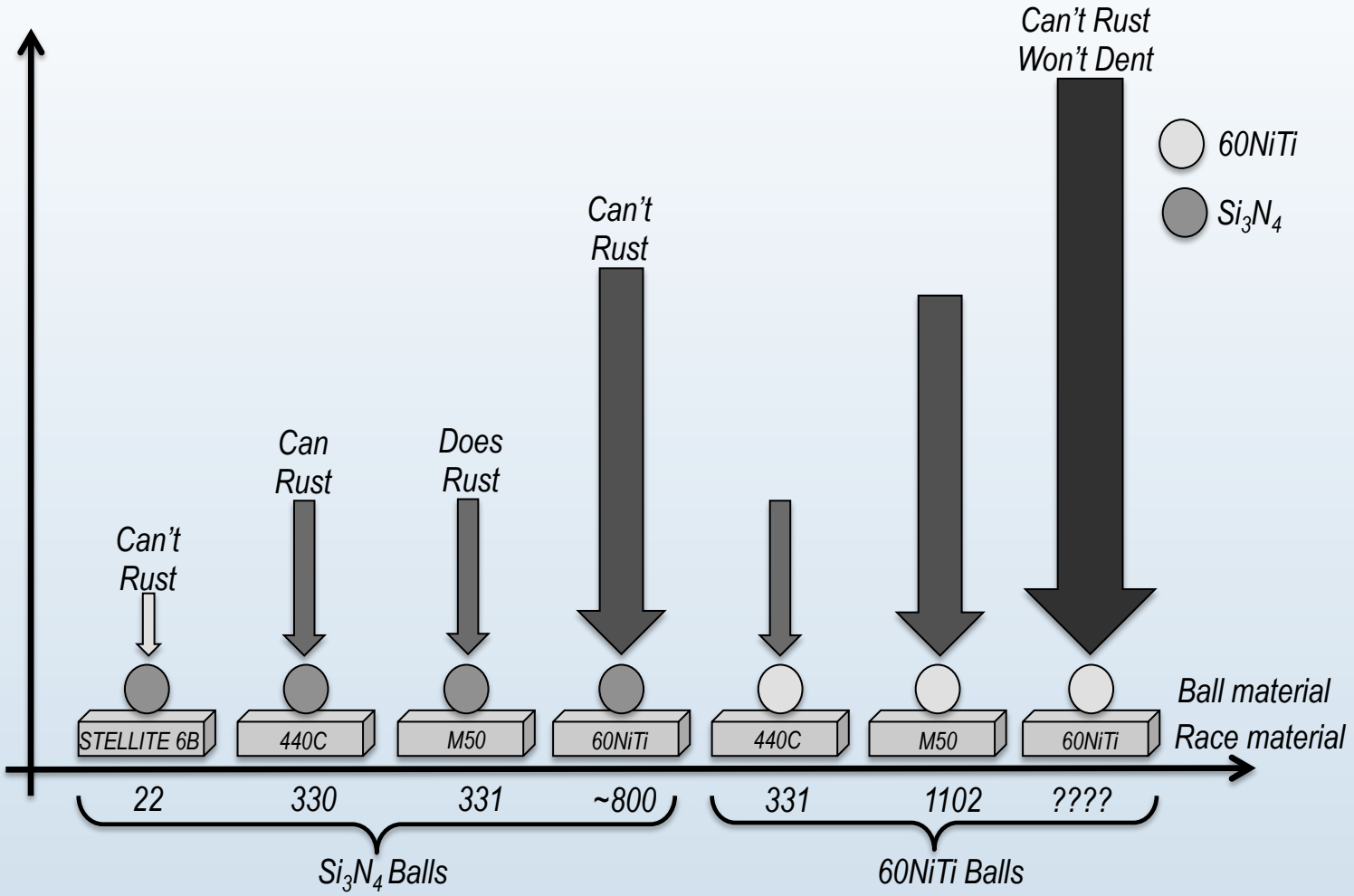
(Si_3N_4 ceramic ball pressed against 60NiTi plate)



60NiTi combines high hardness, reduced stiffness and superelasticity to increase load capacity over other steels dramatically. Immunity to rust is an added bonus!

Damage Threshold Load Capacity: Comparison
(1/2" Diameter ball pressed into plate)

Indent test



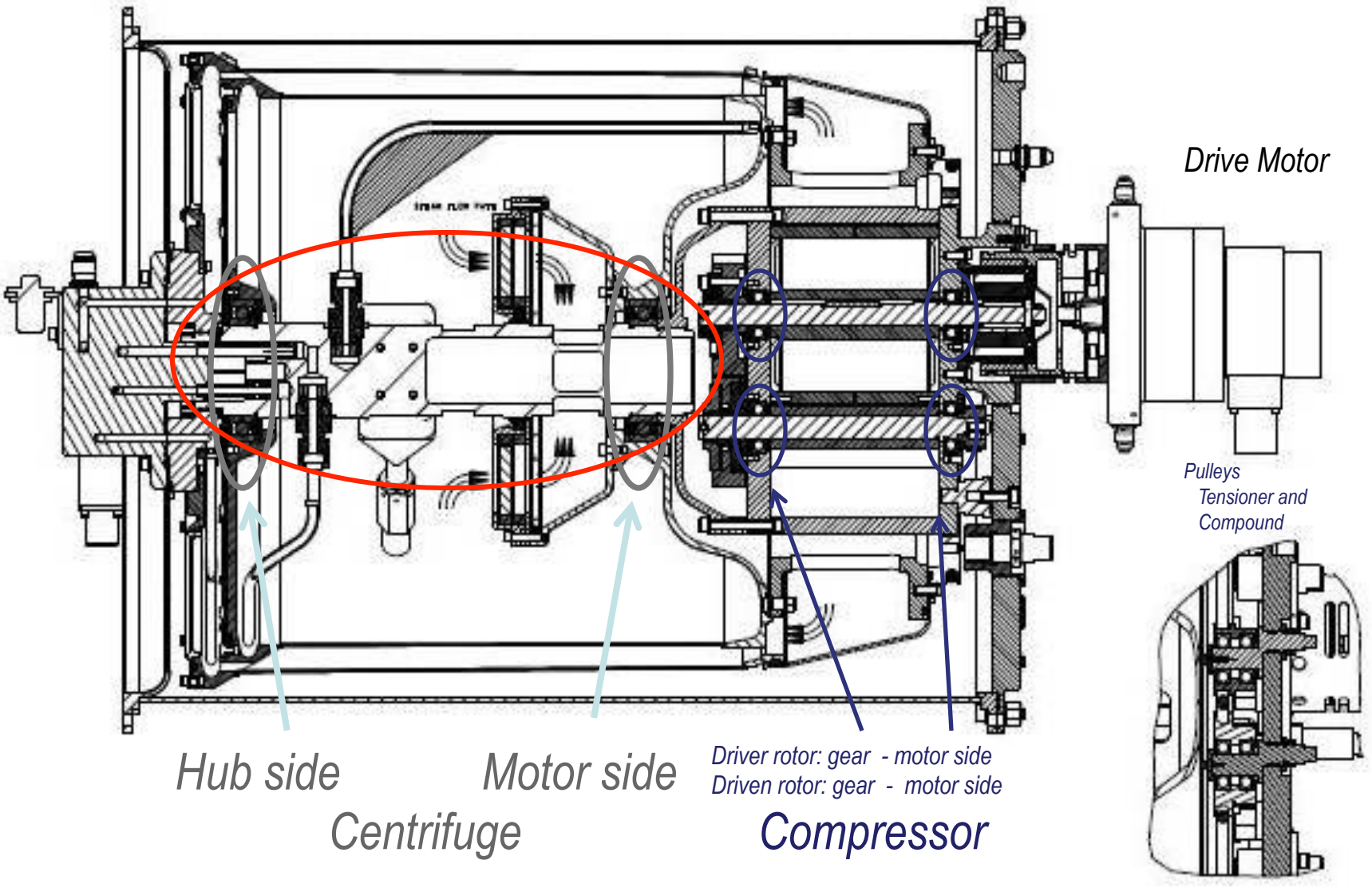
Low modulus + high hardness +superelasticity = extreme load capacity

Pathfinder Bearing Manufacturing

Finished 60NiTi-Hybrid Bearing

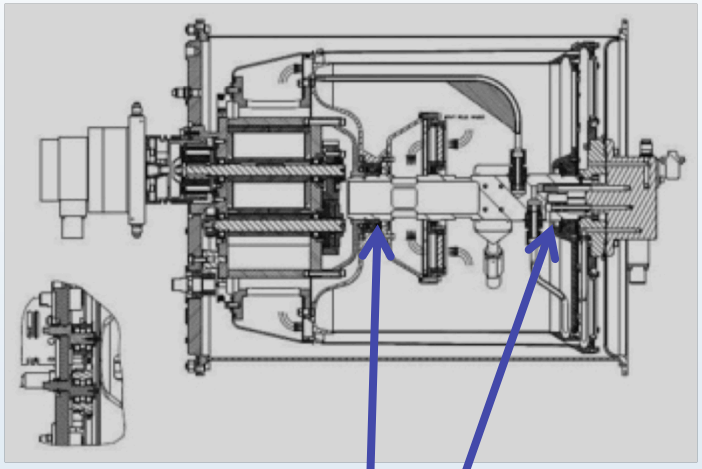
Manufacturing Process is now proven. Does the bearing actually work?

ISS DA Centrifuge Bearings: 60NiTi Application

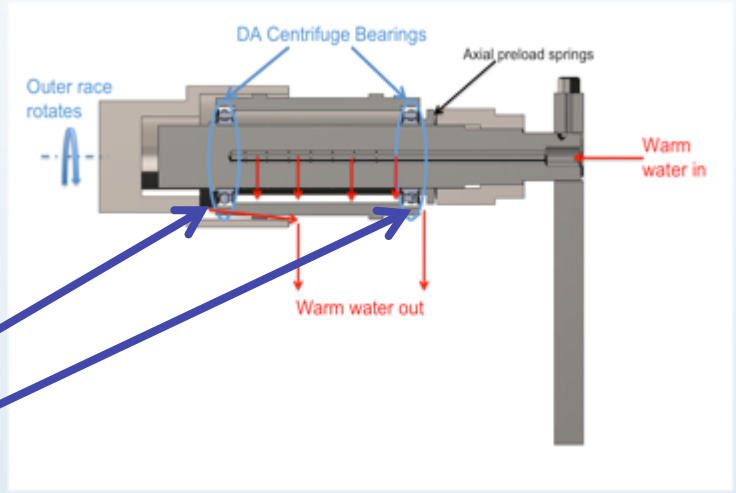


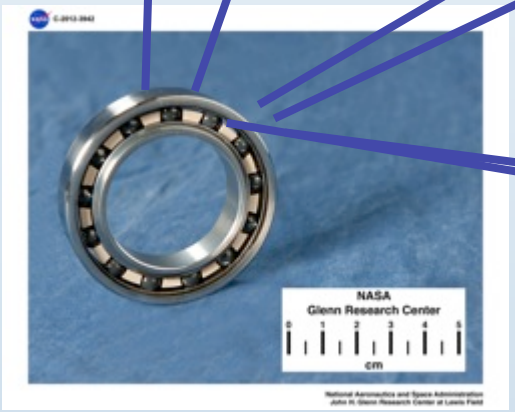
Bearing Testing:
(Warm, wet, slow conditions)

DA Cross Section



DA Urine Processor Simulator



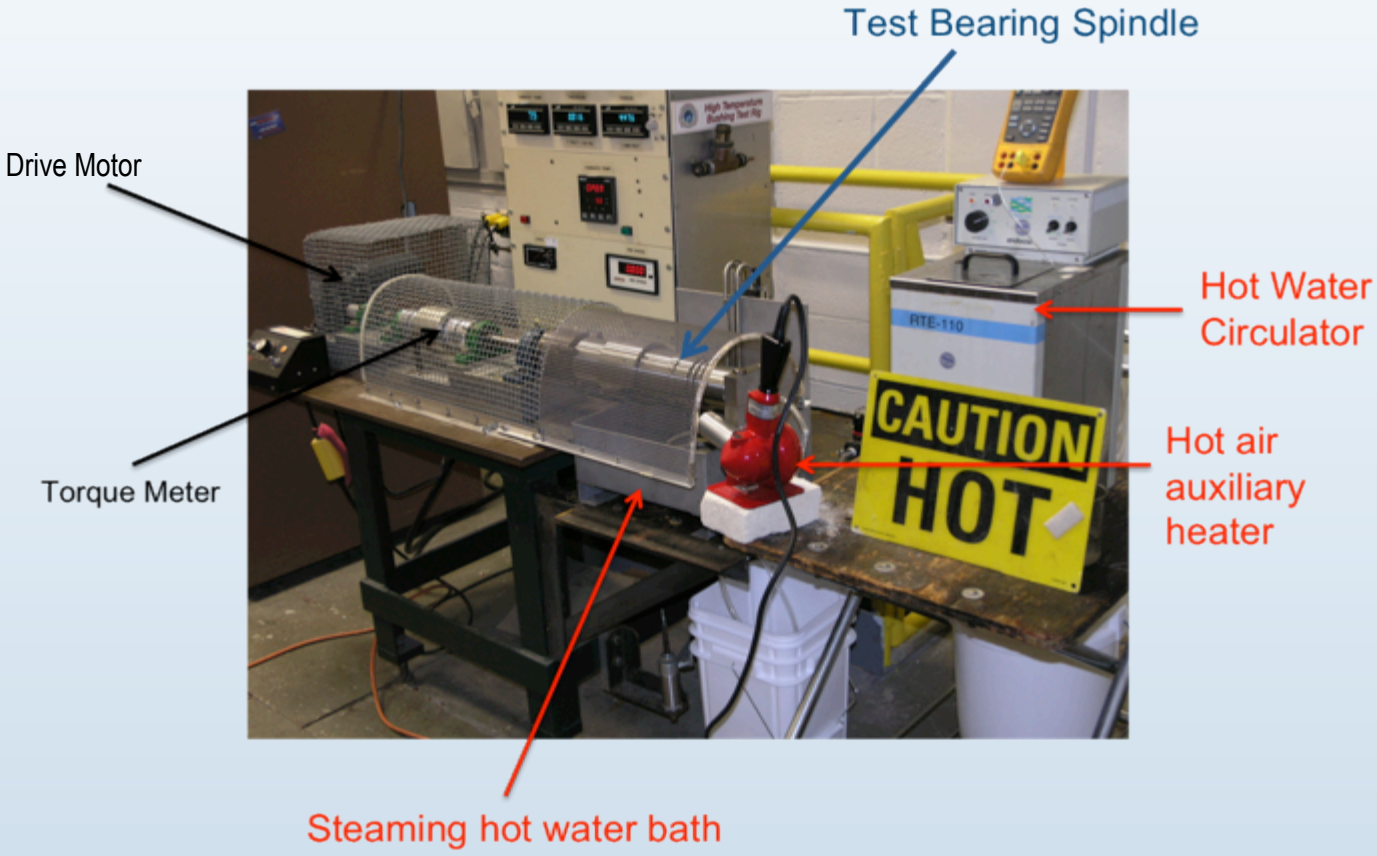


DA Centrifuge Bearing Test Rig
Spindle Components

Speed, load, configuration, temperature and moisture match ISS application.

Bearing Testing:
(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor



Over 10,000 operating hours has been demonstrated.

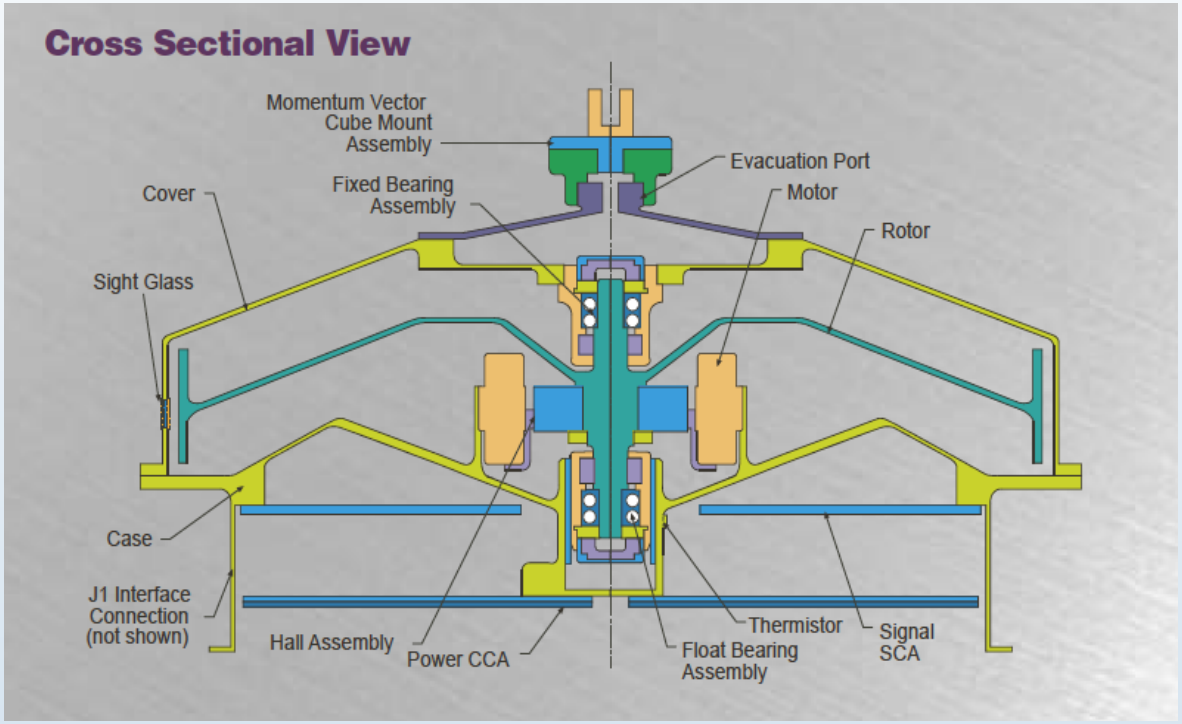
DA Bearing: 60NiTi-Hybrid (50mm)

Post-Test Steel vs. 60NiTi-Hybrid

Test Results: 60NiTi bearings turn but don't rust!

Space Bearing Application: Game Changer

Typical Reaction Wheel Assembly



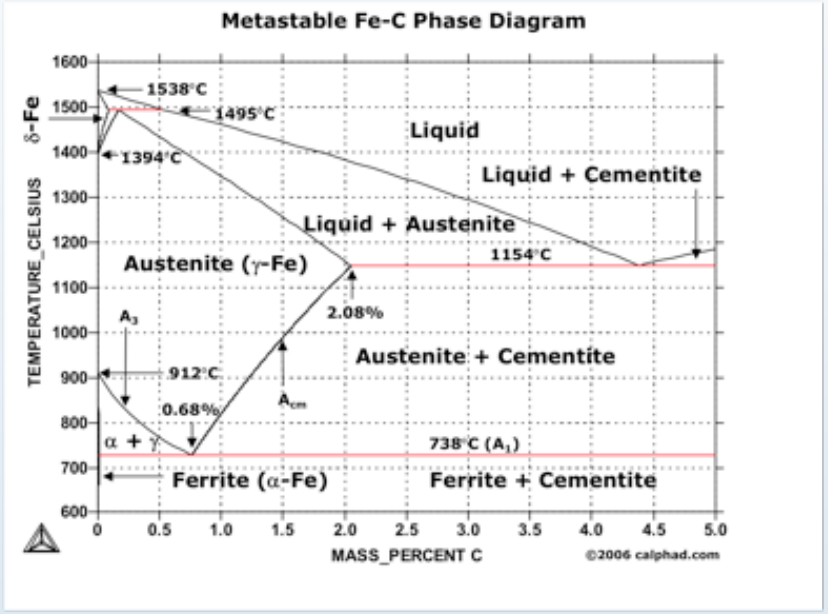
-60NiTi bearing races offer 2x (vs. Rex20) to 5x (440C) improvement.

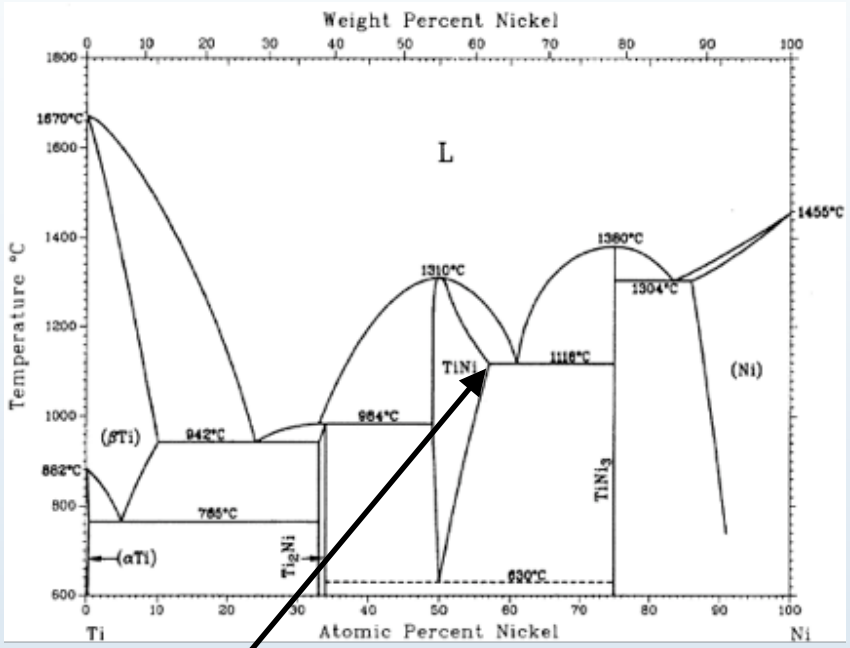
-Adoption of NiTi bearings enables the elimination of half the ball bearings, reducing friction by half with considerable cost and weight savings.

Take Away: 60NiTi is a bearing material!

- Using modern materials and processing methods, 60NiTi can be manufactured into precision bearings.
- Good tribology and corrosion behavior.
- High hardness with low modulus and extremely high “super” elasticity are an unusual and valuable combination of characteristics with major implications to bearing technology.
- Leads to much more robust bearings and mechanical systems. Ideal for industrial, marine, spacecraft and aero bearings and components.

Future View: Materials Design Space





Fe-C system has yielded literally thousands of alloys and variants following centuries of development.

NiTi explorations to date have been limited to a very narrow region.

Though much more R&D remains to commercialize 60NiTi and other superelastic intermetallic materials for use in bearings, gears and other mechanical systems, early indications are very promising.

Nitinol 60: My story began with reluctance

- Success: occurs when preparation meets opportunity
  - Be aware of longstanding technical challenges (corrosion and shock load)
  - Keep an open mind despite preconceptions (e.g. Ti is a poor tribomaterial)
  - Practice saying “yes, but first…” instead of “no” to requests for help
  - Understand that real breakthroughs are not planned, but are fostered
- Collaboration: Two-way street
  - Give a little to get a little
  - Leverage existing resources (test capability, professional contacts, etc.)
- Set Realistic Expectations:
  - Significant advances do not “appear out of the blue”
  - The road to success is filled with detours, dead ends and potholes

Nitinol 60: My story began with reluctance

….included many challenges and surprises..

….and serendipitously opened many new doors..

Thank You!