Resilient and Corrosion-Proof Rolling Element Bearings Made from Ni-Ti Alloys for Aerospace mechanism Applications

Christopher DellaCorte
NASA, Glenn Research Center
Cleveland, Ohio

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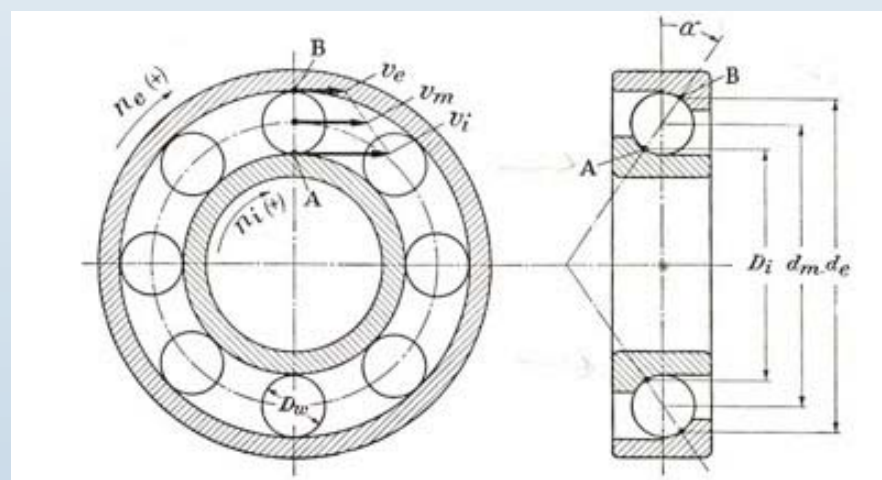
Bearings 101: The what, where, whys and hows

- **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).**
- **Typically made from hard, stiff steel.**

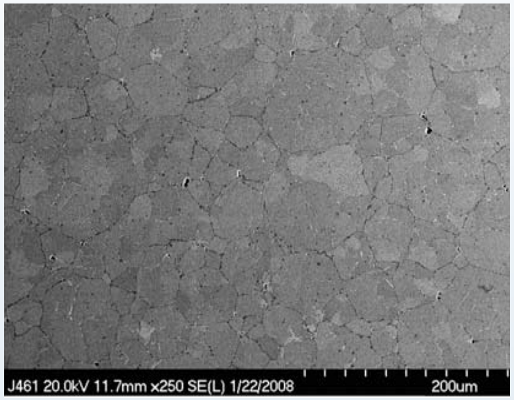


Bearing Material: State-of-Art (SOA)
(Current suite of candidates is severely limited)

- 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.

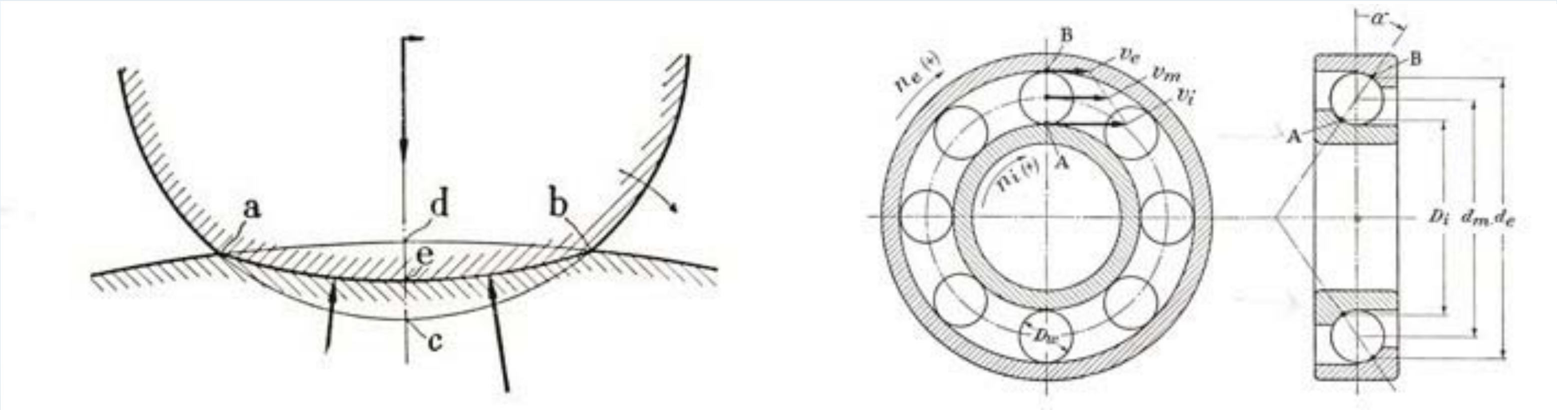


60NiTi microstructure

Highly polished 60NiTi bearing balls

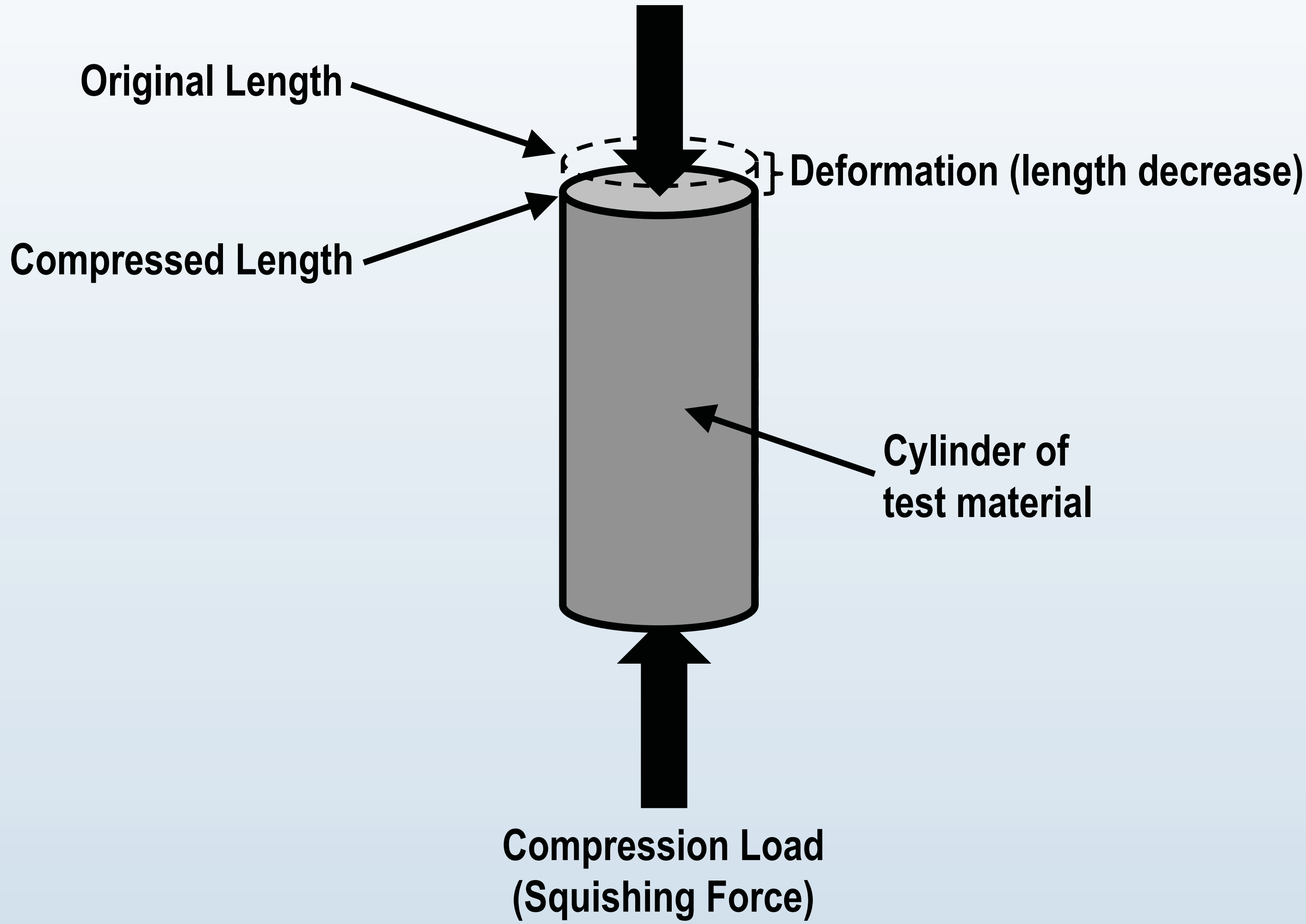
Contact Engineering:
(60NiTi's properties affect contact stresses)

- **When hard surfaces contact**
  - Forces are transmitted at small, concentrated contact points (Hertz).
  - Resulting stresses cause deformations that help "spread the load".
  - Contact area is a function of the geometry, material stiffness and load.
  - High stiffness (modulus) inhibits deformations leading to small contact area and high stresses (contrast with a tire contacting the ground).



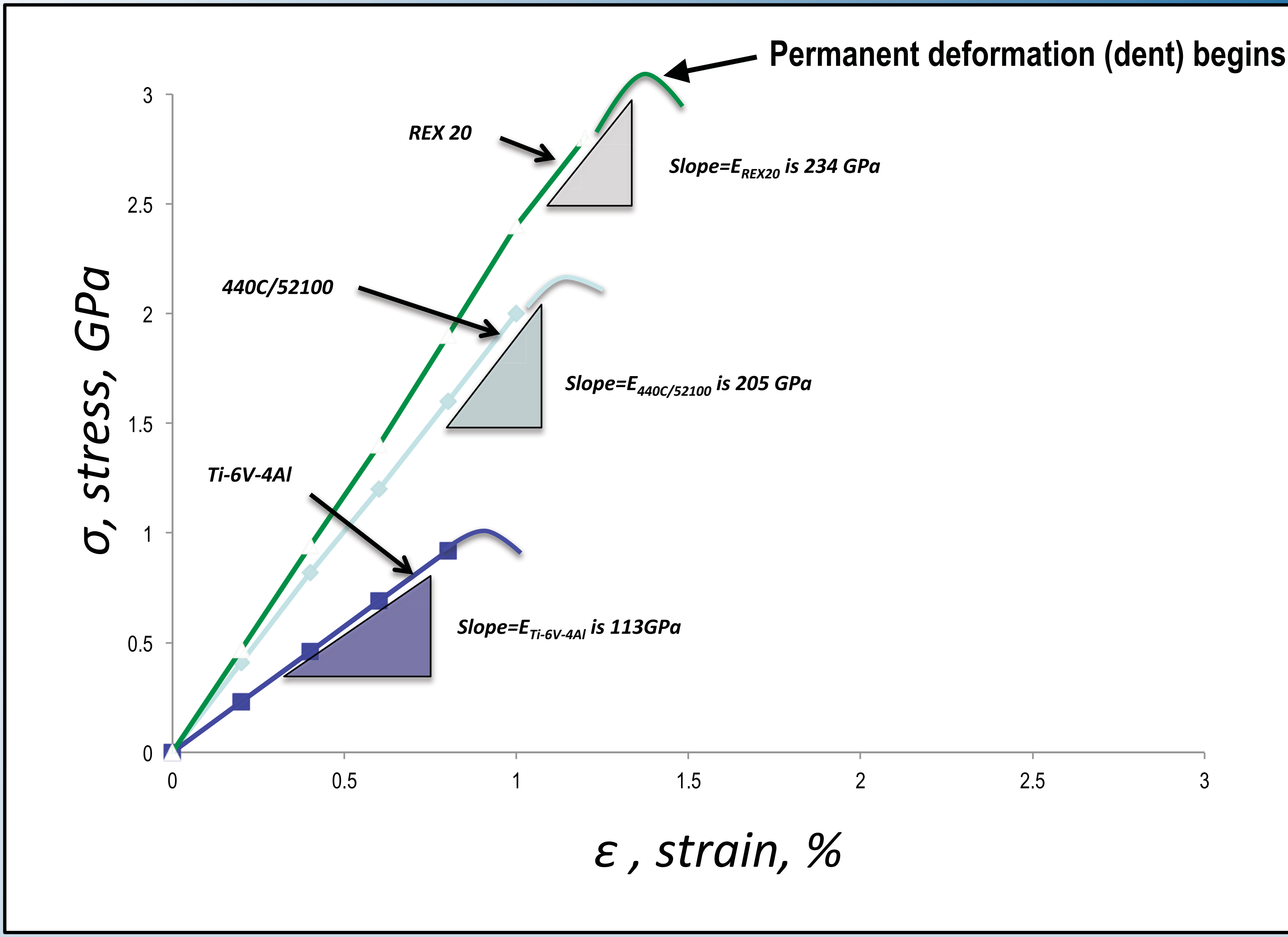
•Hertz stresses are a function of load, radii of surfaces and elastic moduli.
•High stresses lead to dents especially on race surfaces.
•Understanding how materials properties affect race denting requires brief tutorial on stress and strain.

Conventional Metals: Elastic Behavior

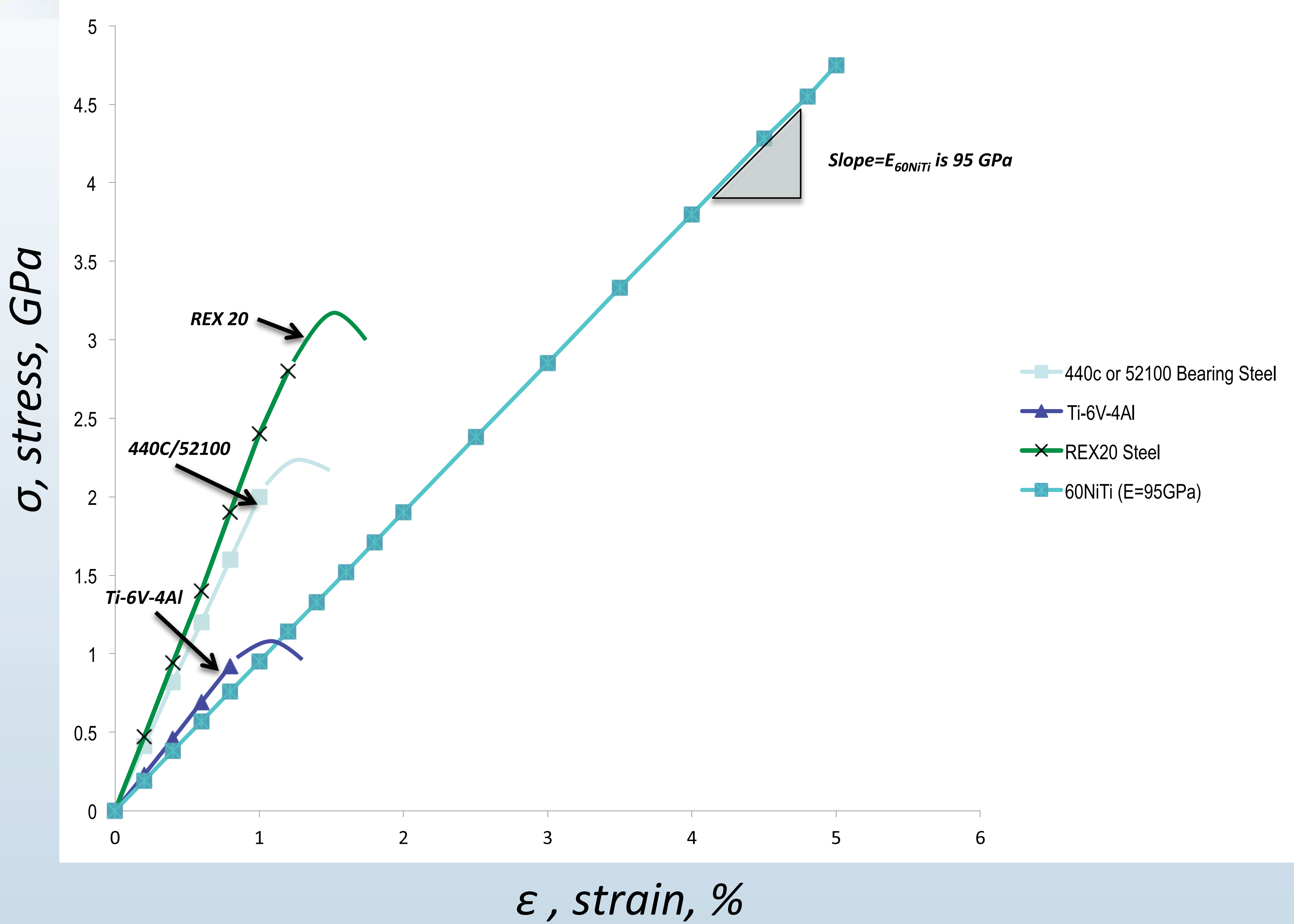


- Deformation is proportional to the elastic modulus (stiffness), not hardness.
- Length is regained when load is removed (elastic) just like a spring.
- If load exceeds yield (plastic) permanent length reduction (dent) occurs.

Conventional Metals: Elastic Behavior

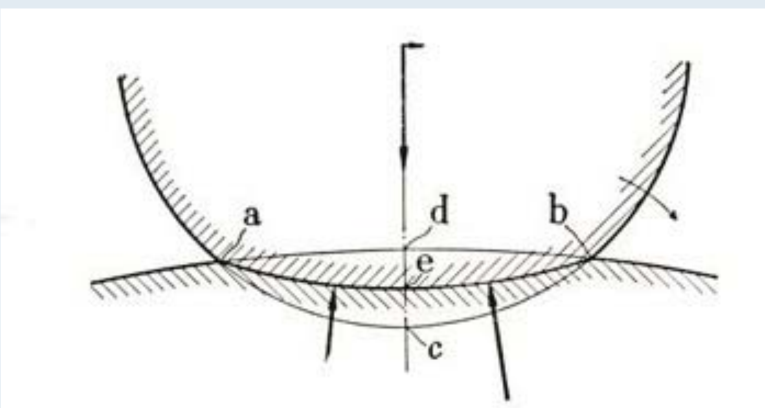


60NiTi: Stress-Strain Behavior

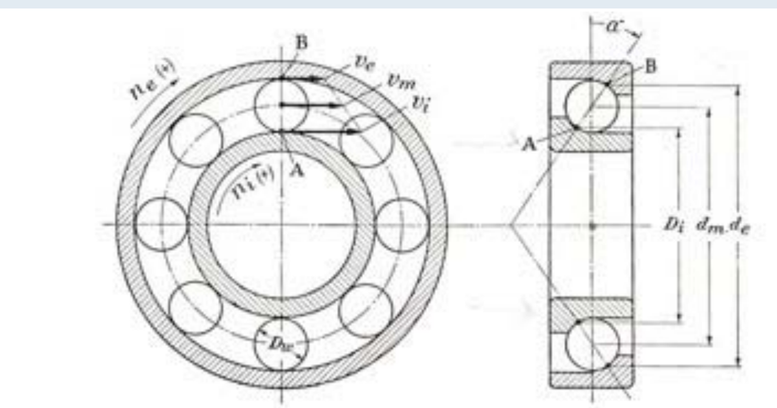


Low Modulus + Hard: A Technical Opportunity

- **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

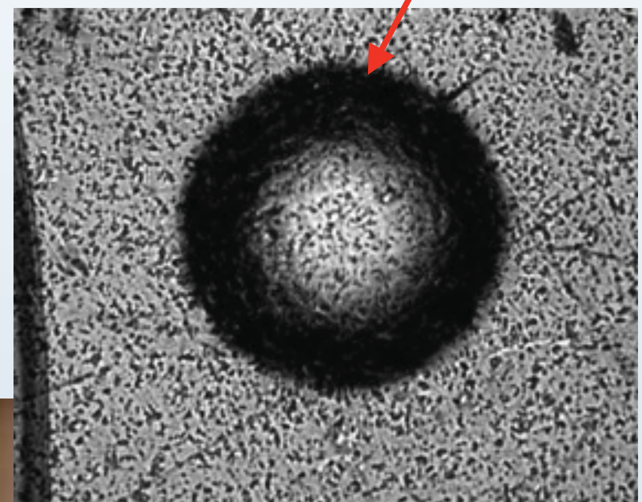


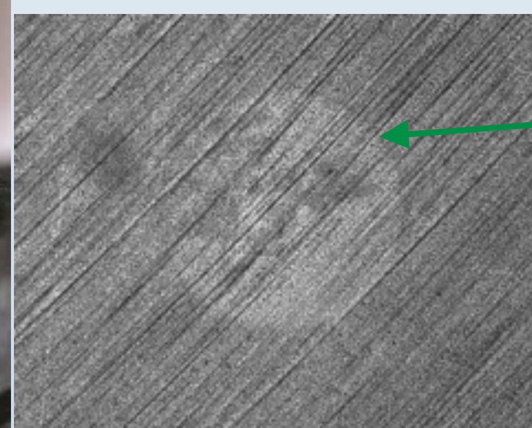
Dents on race surface cause rough running and premature failure

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.

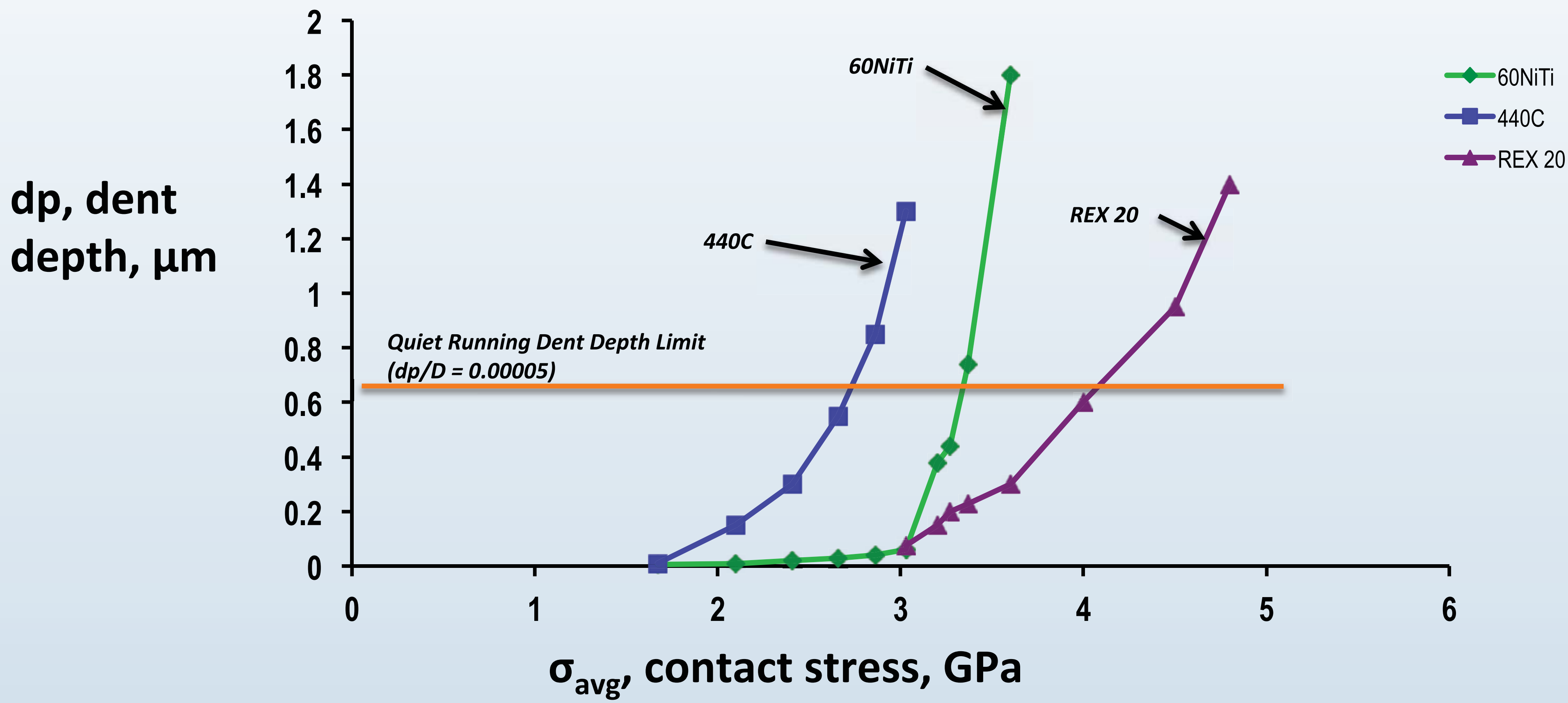




Threshold load visible dent.

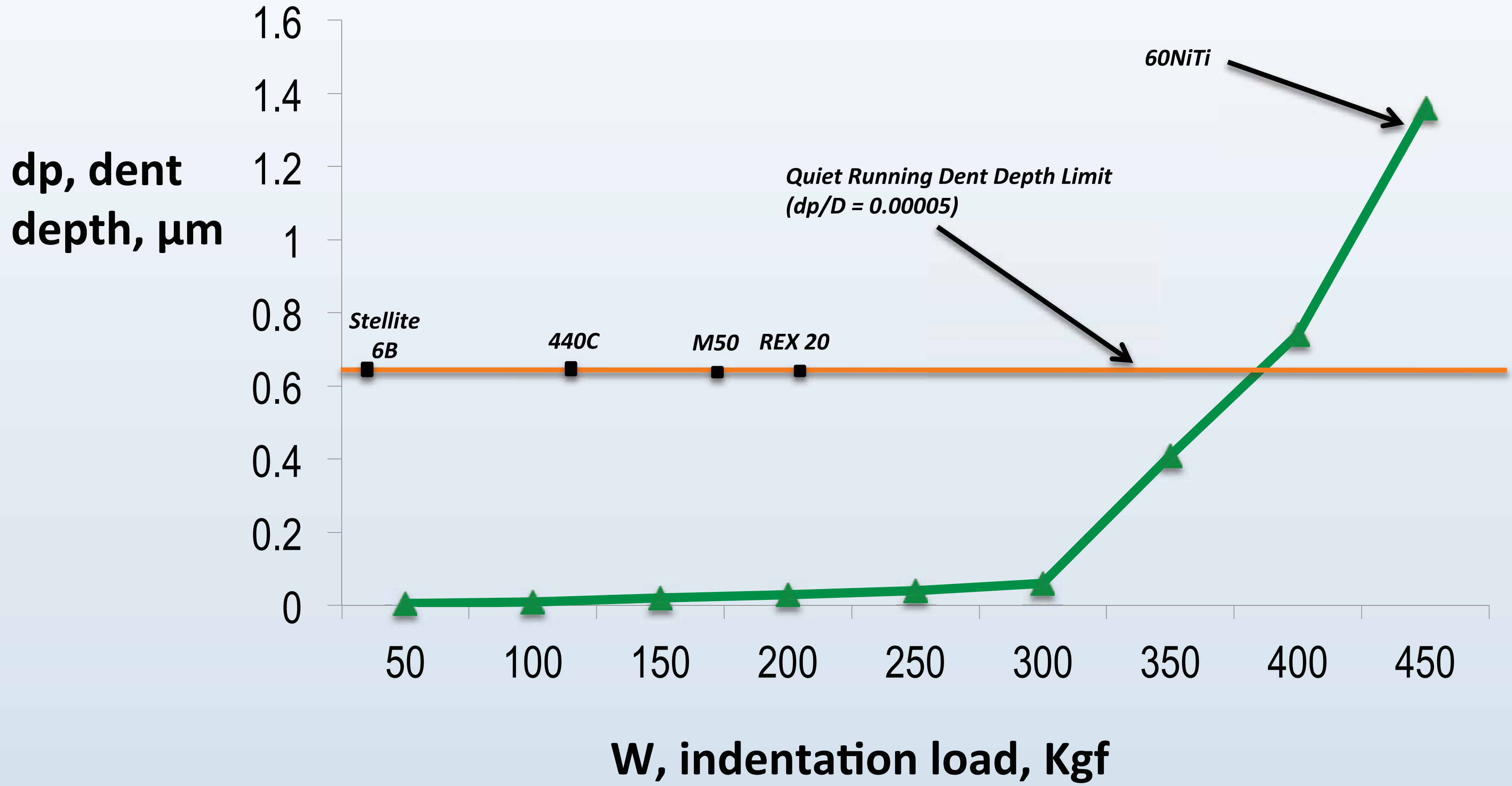
Dent Depth vs. Hertz Contact Stress

(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)



Dent Depth vs. Load

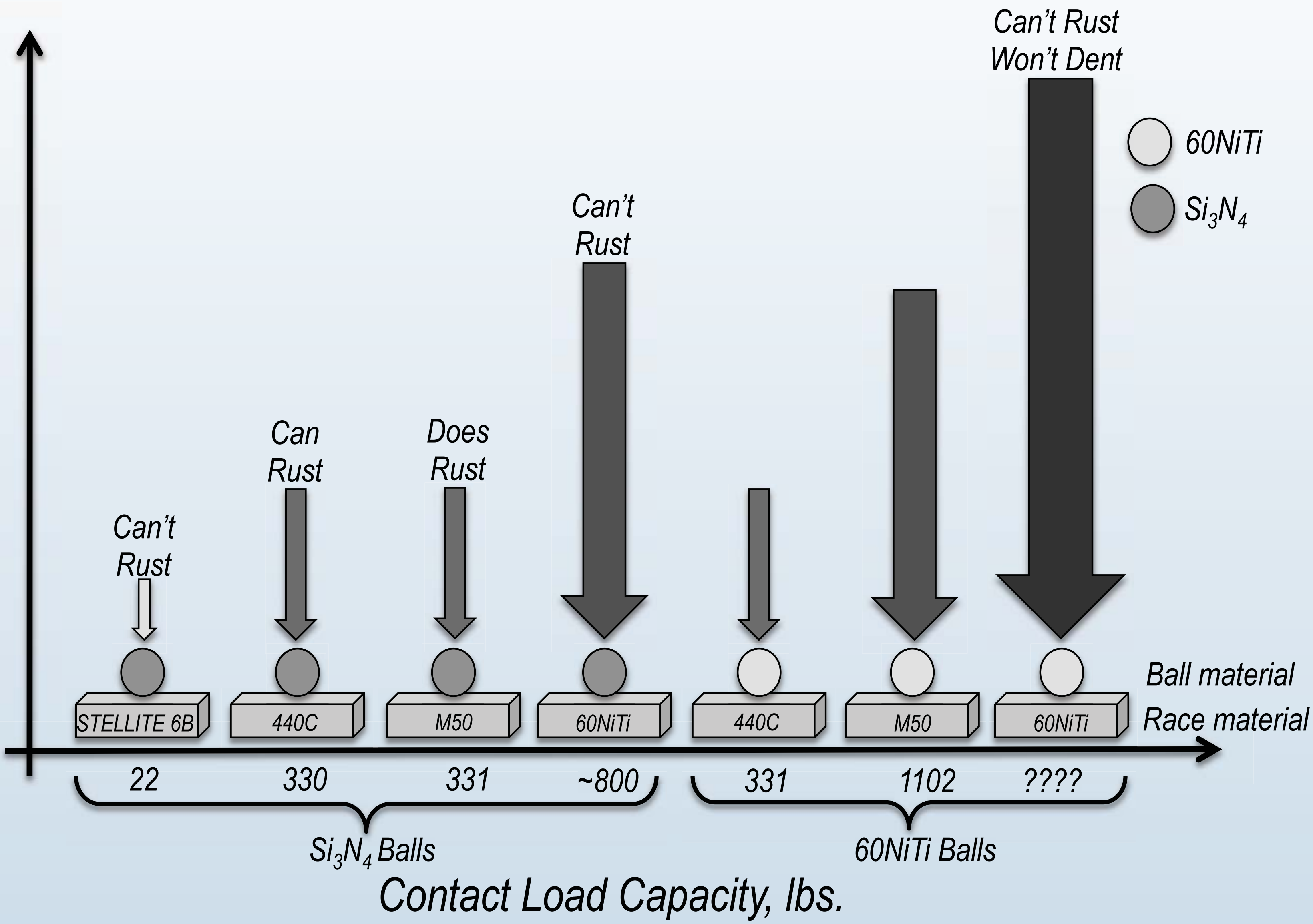
(Si_3N_4 ceramic ball pressed against 60NiTi plate)



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

Bearing Manufacturing: 2nd half of the puzzle

60NiTi Ingot Prototype

60NiTi Ingot Slice

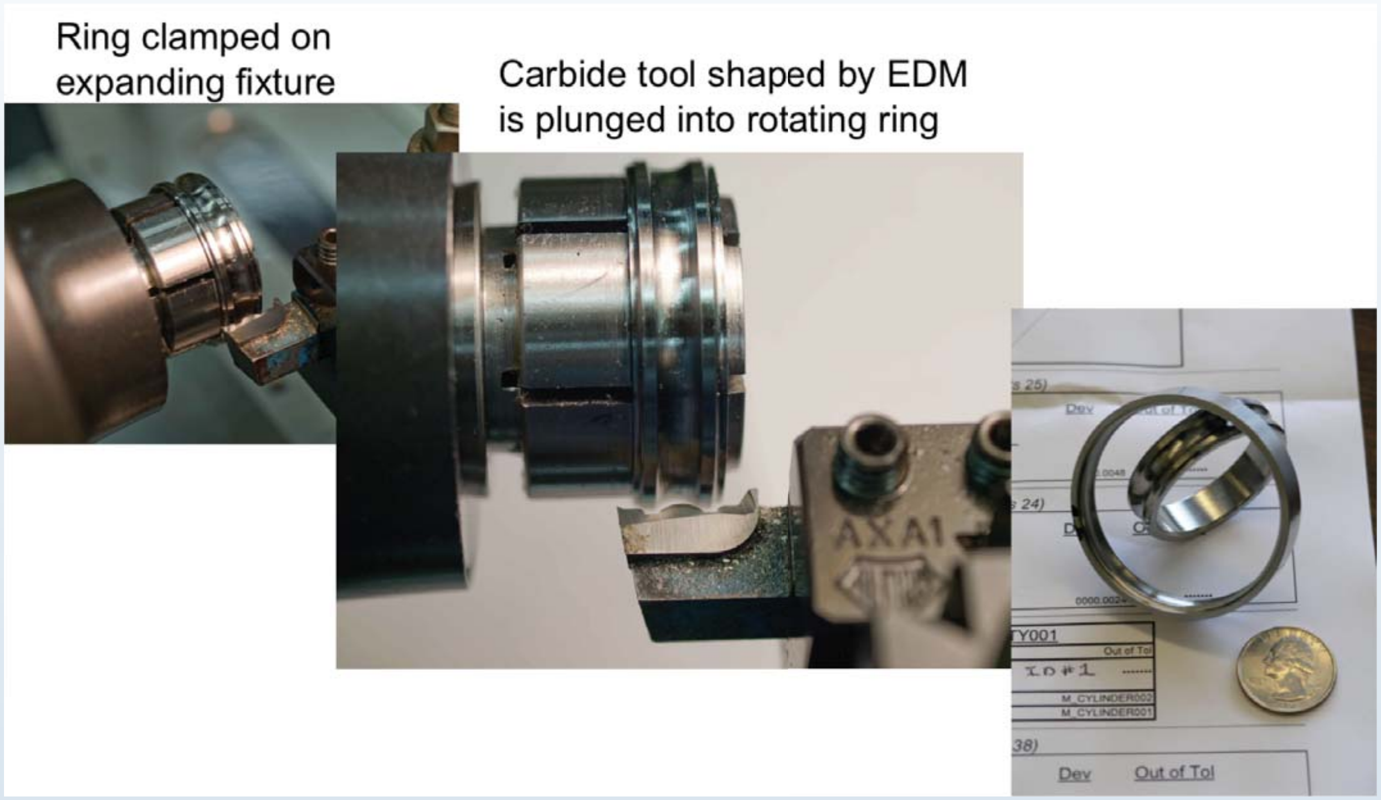
Wire Cut Blanks

QC Metallography

Microstructure and quality verified during manufacture.

Now the material is ready for shaping into bearing races.

Bearing Manufacturing: Race Turning Details



Next Step: Heat treating the races to increase hardness.

Bearing Manufacturing: Heat treatment

Unrestrained Races Distorted

Inconel race fixtures
(vented to allow quenching)

Process yields flat, round,
hardened races

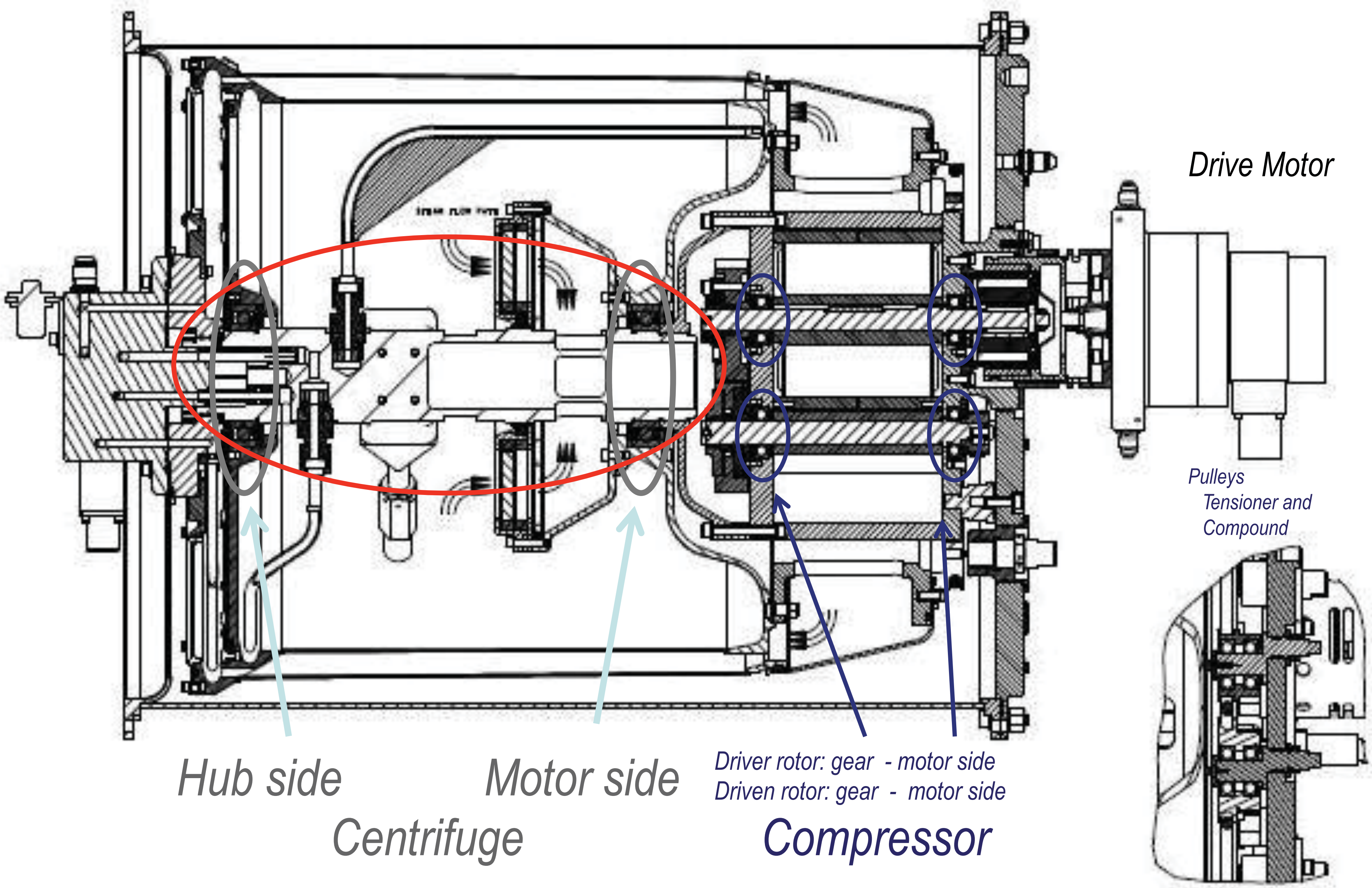
Final steps include finish grind, polish and assembly.

Pathfinder Bearing Manufacturing

Finished 60NiTi-Hybrid Bearing

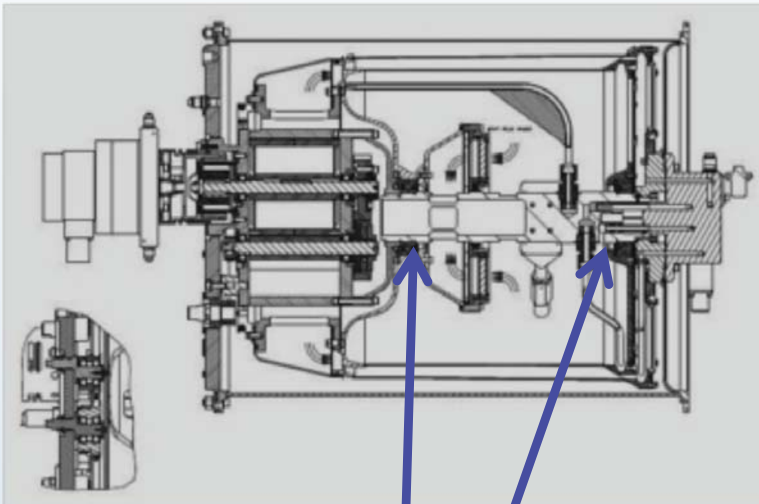
Manufacturing Process is now proven. Does the bearing actually work?

ISS DA Centrifuge Bearings: 60NiTi Application

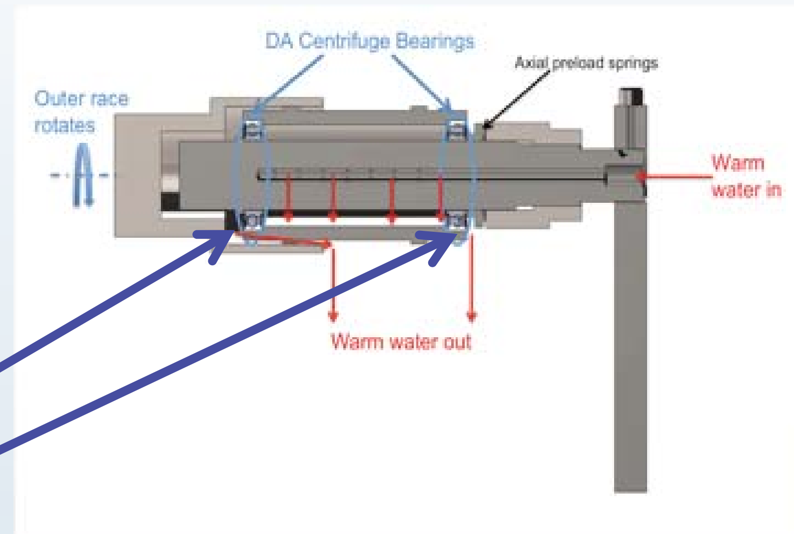


Bearing Testing:
(Warm, wet, slow conditions)

DA Cross Section



DA Urine Processor Simulator

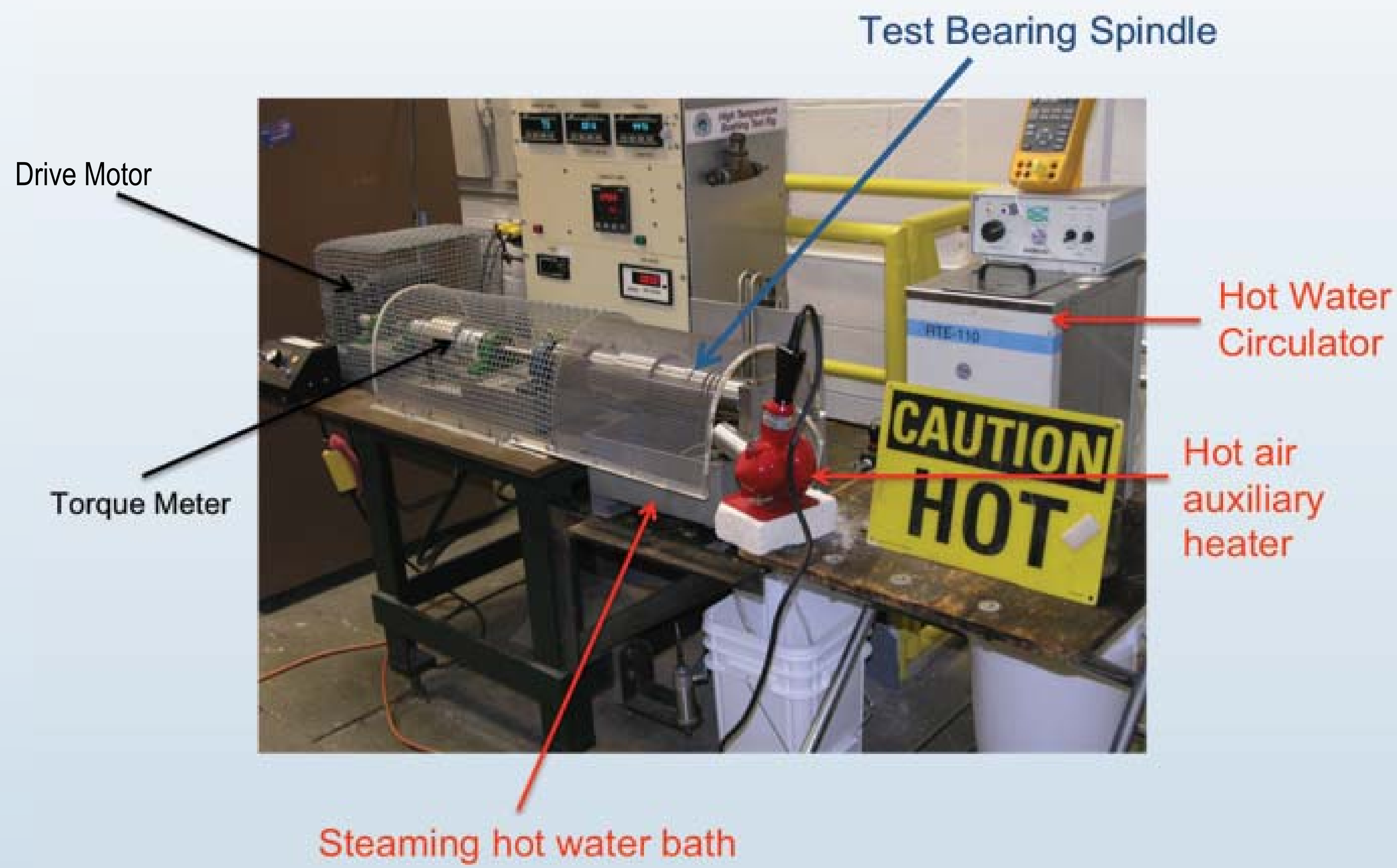


DA Centrifuge Bearing Test Rig
Spindle Components

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

Bearing Testing:
(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor



Short term (20 hour) tests run to prove operations.

DA Bearing: 60NiTi-Hybrid (50mm)

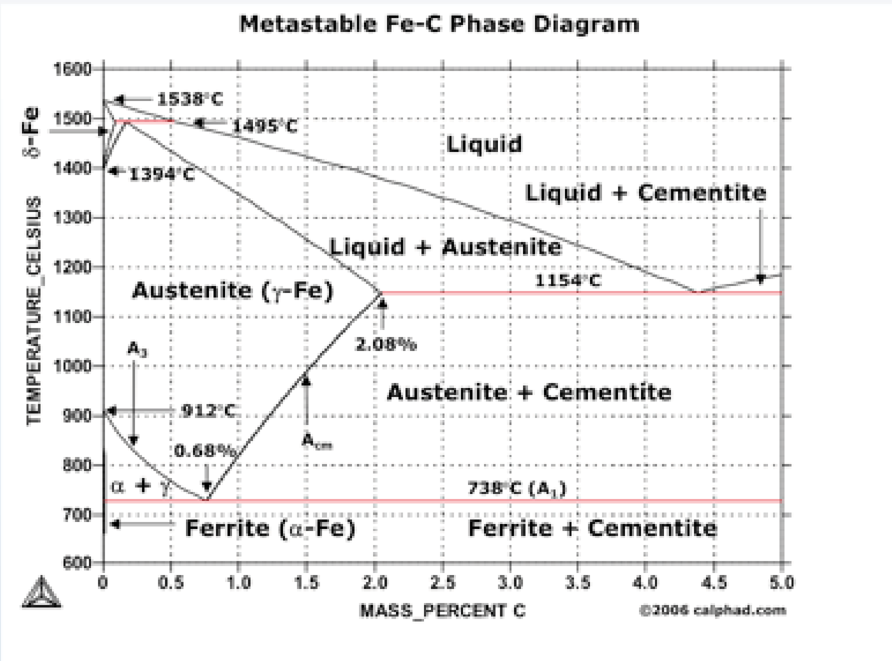
Post-Test Steel vs. 60NiTi-Hybrid

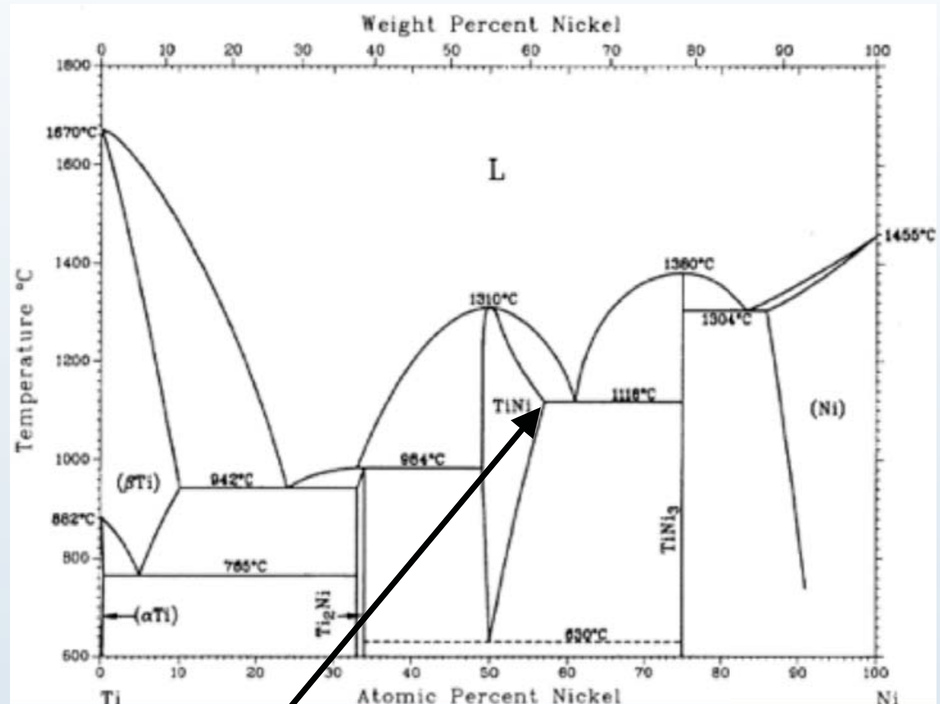
Test Results: 60NiTi bearings turn but don't rust!

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.

Closing Thoughts: 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 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.

Thank You!

Space Tribology Challenges on-board the International Space Station (ISS)

The Ultimate Space Technology Development Platform

Dr. Christopher DellaCorte

Senior Technologist, Tribology and Rotating Machinery

NASA, Glenn

Cleveland, Ohio

USA

__University of Arkansas__

February 25th, 2015

ISS-Background:

- International Space Station (ISS)
  - Solar powered laboratory platform
  - Low earth orbit (~250 miles above surface)
  - One complete orbit takes 90 minutes
  - Solar panels continually rotate to track the sun and keep the station "facing the ground".
  - Unique up-mass/down-mass opportunities for research and development.

ISS-Background: Environment

- ISS provides Jekyll/Hyde zero-g environment
  - Outside ISS: hard space vacuum, atomic oxygen and UV radiation exposure, -100 to +100°C temperature swings.
  - Inside ISS: Nominal earth atmosphere, stringent health/safety requirements, unique tribology challenges (e.g., life support system machines).
  - General: Zero-g thwarts normal fluid flows (convection, drainage, etc.),

ISS-Background: Key References

- **Excellent Recent Space Tribology Topical Review:**
  - **E.W. Roberts: "Space Tribology: Its Role in Spacecraft Mechanisms," J. Phys. D: Appl. Phys. 45 (2012)503001.**

IOP Publishing — Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. 45 (2012) 503001 (17pp) — doi:10.1088/0022-3727/45/50/503001

TOPICAL REVIEW

Space tribology: its role in spacecraft mechanisms

E W Roberts

ESTL, ESR Technology, Part of the Hyder Consulting Group, Birchwood Park, Risley, Warrington, Cheshire, UK WA3 6FW

E-mail: emyr.roberts@esrtechnology.com

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Abstract
The subject of tribology encompasses the friction, wear and lubrication of mechanical components such as bearings and gears. Tribological practices are aimed at ensuring that such components operate with high efficiency (low friction) and achieve long lives. On spacecraft mechanisms the route to achieving these goals brings its own unique challenges. This review describes the problems posed by the space environment, the types of tribological component used on spacecraft and the approaches taken to their lubrication. It is shown that in many instances lubrication needs can be met by synthetic oils having exceedingly low volatilities, but that at temperature extremes the only means of reducing friction and wear is by solid lubrication. As the demands placed on space engineering increase, innovatory approaches will be needed to solve future tribological problems. The direction that future developments might take is anticipated and discussed.

(Some figures may appear in colour only in the online journal)

1. Introduction

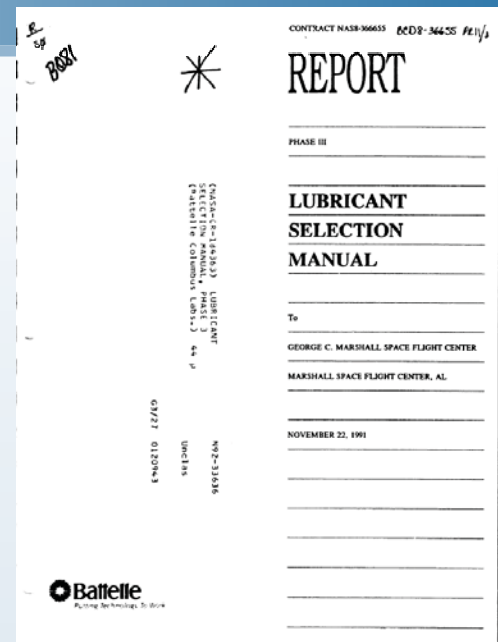
The success of spacecraft missions depends critically on the reliability of mechanisms and this in turn is dependent on the life and functionality of their component parts. The management of friction and wear processes in those parts that have a tribological element is the subject of space tribology.

As an illustration, a solar-array-drive mechanism (SADM) has the function of rotating an array of solar cells so that they continuously face the sun thus maximizing the generation of the electrical power needed to operate the satellite. Typically, rotation is achieved by means of an electromechanical assembly comprising a motor, gearbox and support bearings whilst transfer of electrical power across the rotating junction is accomplished using slip-rings. Should any of these components fail—resulting either in an inability to rotate the arrays or transfer electrical power from them—the mission may well be lost.

The components' design and lubrication must be sufficiently robust to withstand the rigours of the launch environment and the thermal extremes and vacuum conditions of the space environment. During launch high levels of random vibration and acoustic noise induce high transient loads and fretting motion at mechanical interfaces which can, in the absence of precautionary measures, cause surfaces to deform plastically and/or cold weld. Such damage is irreversible. On route to its final destination in space, a spacecraft mechanism quickly depressurises and approaches a vacuum level which is a balance between the rate of evacuation of the mechanism and the rate of outgassing of materials within the mechanism. For the aforementioned SADM operating on a geostationary satellite the pressure within is in the order 10^{-7} mbar (comprising mostly water vapour) [1]—somewhat higher than that 'outside' (10^{-13} mbar). The thermal environment in which mechanisms operate can be one of extremes: from cryogenic temperatures (for deep space missions and those involving cooled infrared devices) to elevated temperatures (e.g. 250 °C for Mercury-orbiting spacecraft). Few lubricants remain effective when exposed to this combination of high vacuum and temperature extremes. Radiation (comprising intense fluxes of electrons and protons) is another environmental factor that can degrade lubricants: however, in most instances lubricants are shielded from potentially harmful effects by the surrounding metal.

ISS-Background: Key References

- <u>Foundational ISS Tribology Papers</u>:
  - J.W. Kannel, J.A. Lowry, and K.F. Dufrane: “Lubricant Selection Manual,” NASA CR-184363, November, 1991.
  - L.J. Leger, and K.F. Dufrane: “Space Station Lubrication Considerations,” proceedings of the 21st Aerospace Mechanisms Symposium, NASA CP-2470, April 29-May 1, 1987, pp. 285-294


REPORT

PHASE III

LUBRICANT SELECTION MANUAL

To

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MARSHALL SPACE FLIGHT CENTER, AL

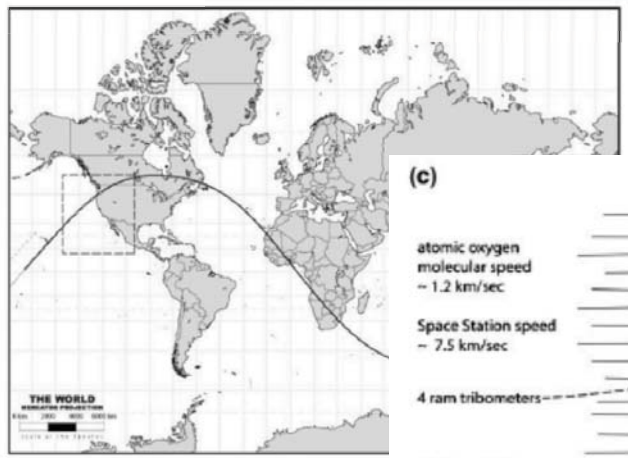
NOVEMBER 22, 1991

Battelle

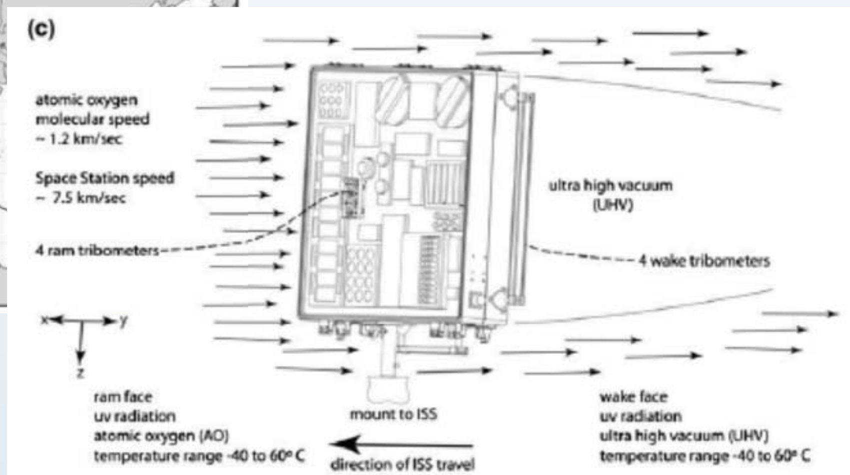
ISS-Environment: Tribology Impact

- ISS provides Jekyll/Hyde zero-g environment
  - Outside ISS: Extensive use of vacuum compatible grease, solid film lubricants, radiation shielding.
  - Inside ISS: Grease, PTFE based solid lubricants, fire/toxicity/odor concerns.
  - General: Wear debris minimization and control, maintenance-free are key drivers. Active thermal control/cooling is norm.

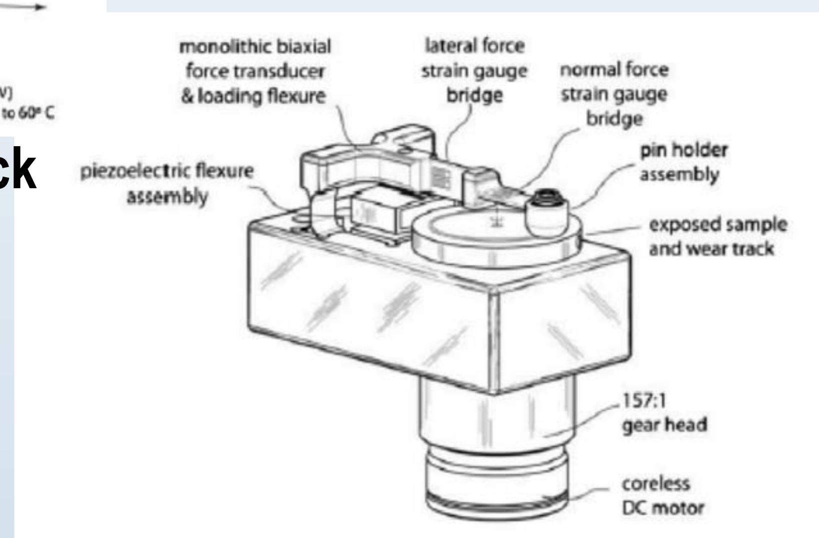
MISSE-7: ISS Tribology Experiments



ISS Orbits



Eight POD units in MISSE Rack



Pin-on-disk tribometer unit

Candidate space lubricants

	Disk sample/coating	Ball material	Disk substrate
RAM	MoS_2/Au/Sb_2O_3	440C	304 Stainless Steel
	YSZ/Au/MoS_2/C	440C	304 Stainless Steel
	PTFE/nano-Al_2O_3	440C	Bulk PTFE/Al_2O_3
	Gold	Ruby	Bulk gold
Wake	MoS_2/Sb_2O_3/Graphite	440C	304 Stainless Steel
	PTFE/nano-Al_2O_3	440C	Bulk PTFE/Al_2O_3
	YSZ/Au/MoS_2/C	440C	304 Stainless Steel
	DLC/SiO-doped	440C	304 Stainless Steel

- Univ. of FL (Krick & Sawyer)

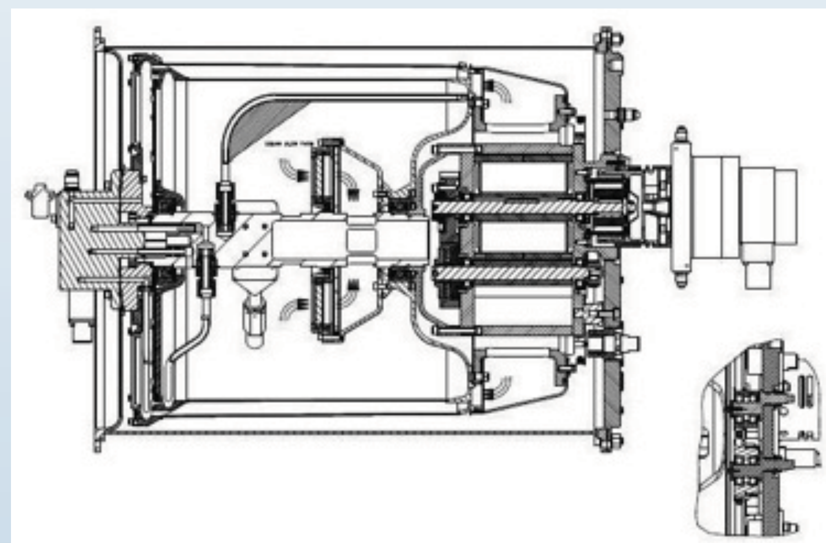
ISS: Layout, scale and scope

- Is large, ~100 meters long, stiff backbone truss, terminated by Solar Panels (PV) array "wings".
- Many moving mechanisms and systems.
- Two specific tribology problems epitomize the challenges.

ISS: Tribology Challenge Examples

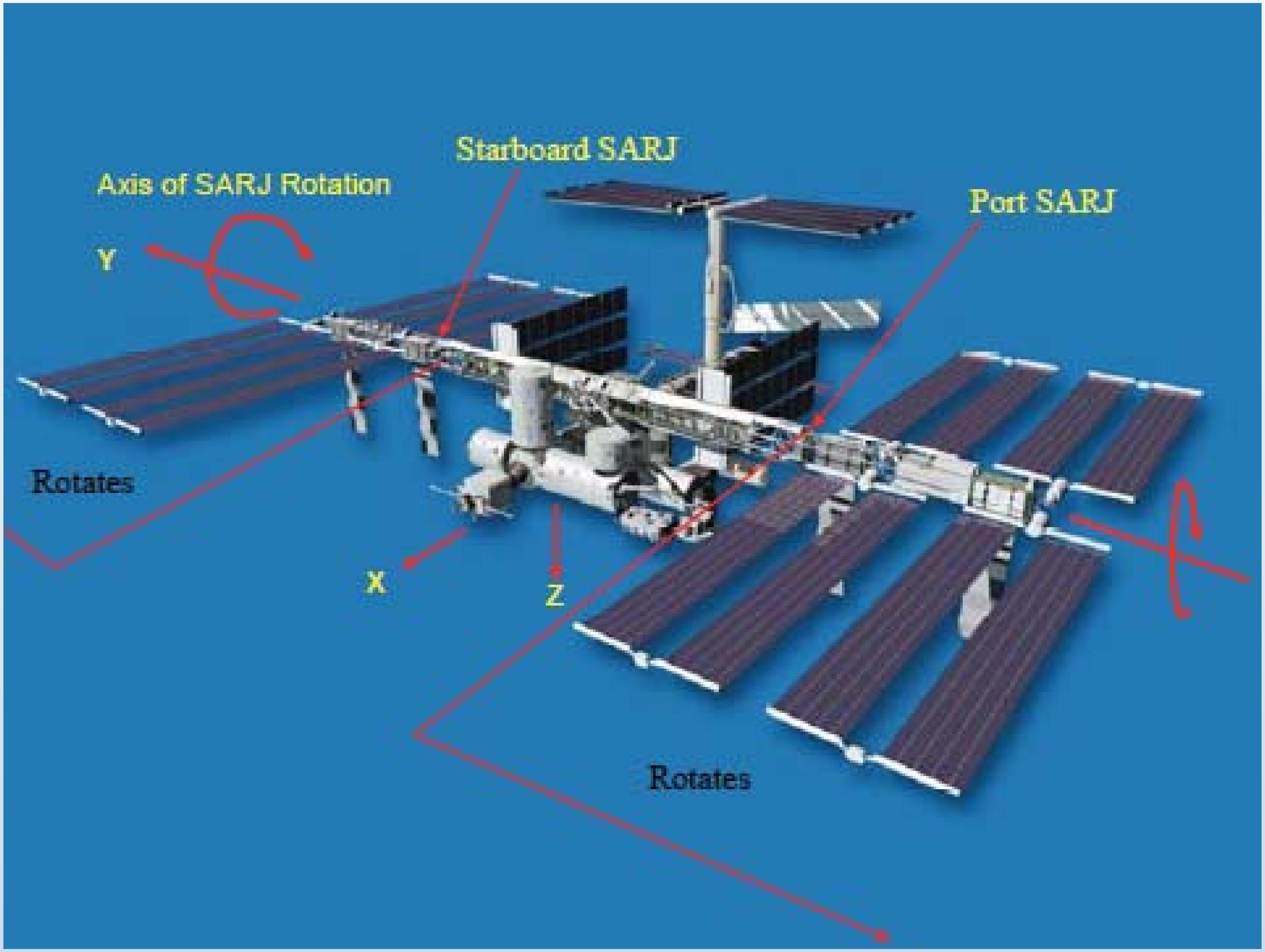
- <u>SARJ Bearing Failure</u>:
  - In space environment outside.
  - Continuous slow rotation
  - Vital to ISS operation. Failure not an option.

- <u>ECLSS Distillation Assembly</u>:
  - Inside ISS, warm, wet, corrosive environment.
  - Intermittent use.
  - Changes/trials possible.



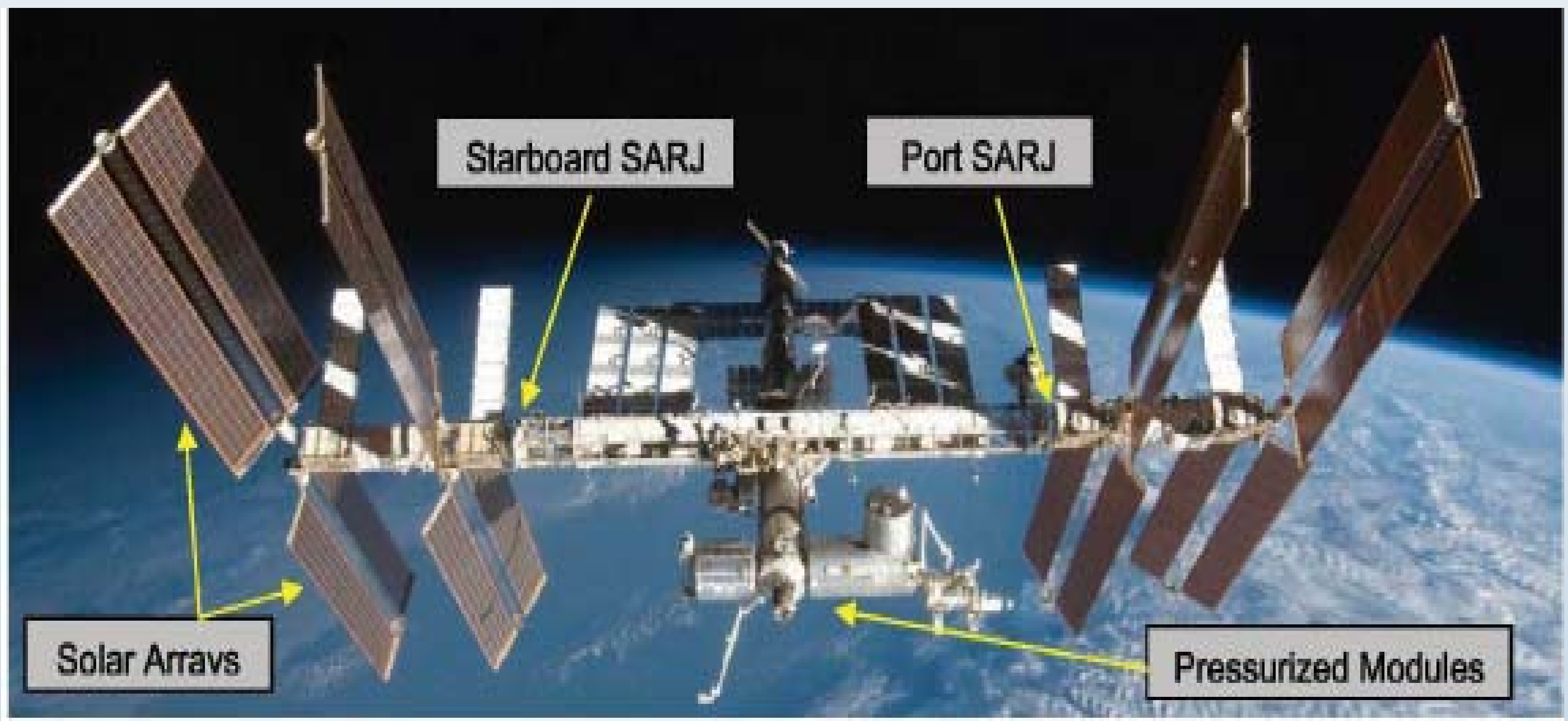
ISS: Layout and terminology

- Truss has two sides, port and starboard.



SARJ Background-ISS

- Basic SARJ functional operation
  - SARJs must be stiff, smooth and reliable.
  - SARJs are halted during EVAs and shuttle docking

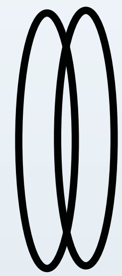


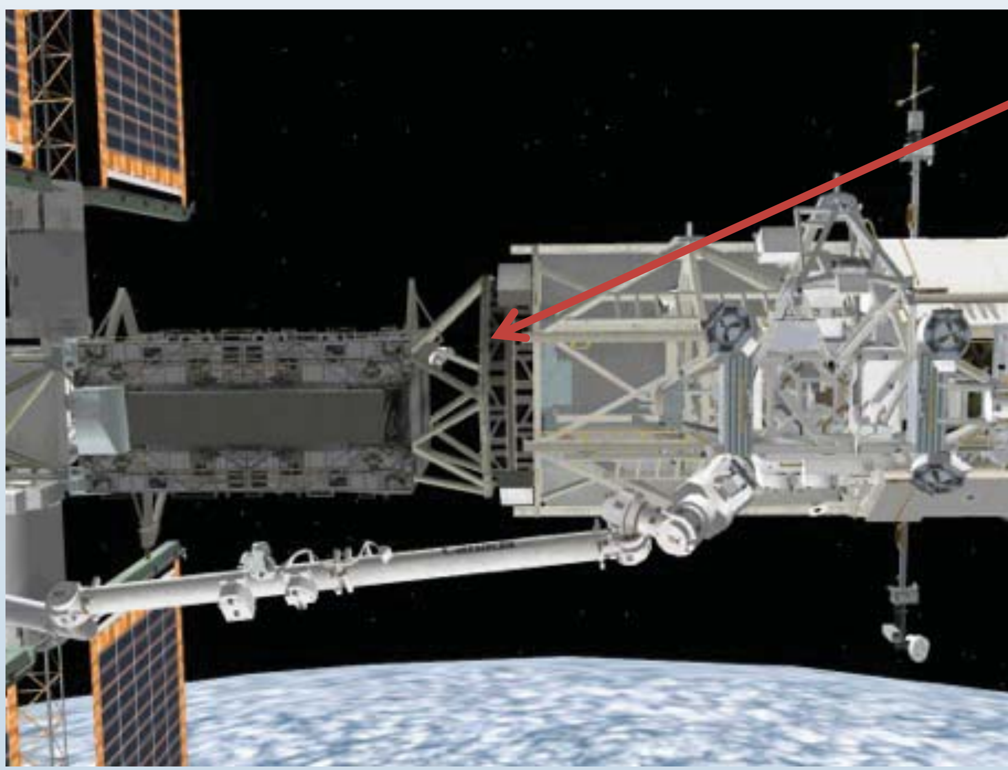
SARJ Requirements

- SARJs are required:
  - Last thirty years without maintenance
  - Cause no vibrations
  - Be replaceable and redundant
  - Operate in the vacuum of space bombarded by atomic oxygen and possibly micrometeorite impact.
- SARJs are large, unique mechanisms
  - Cannot be fully and accurately tested on the ground.

SARJ Hardware

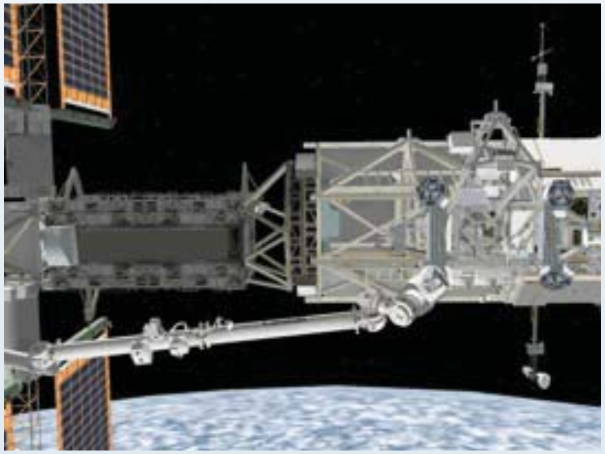
- 10 foot diameter bearing comprised from two rings (races) in a side-by-side arrangement.
- Incorporates ring gear drive mechanism
- Includes centrally located slip ring to transmit power and data to habitation modules.

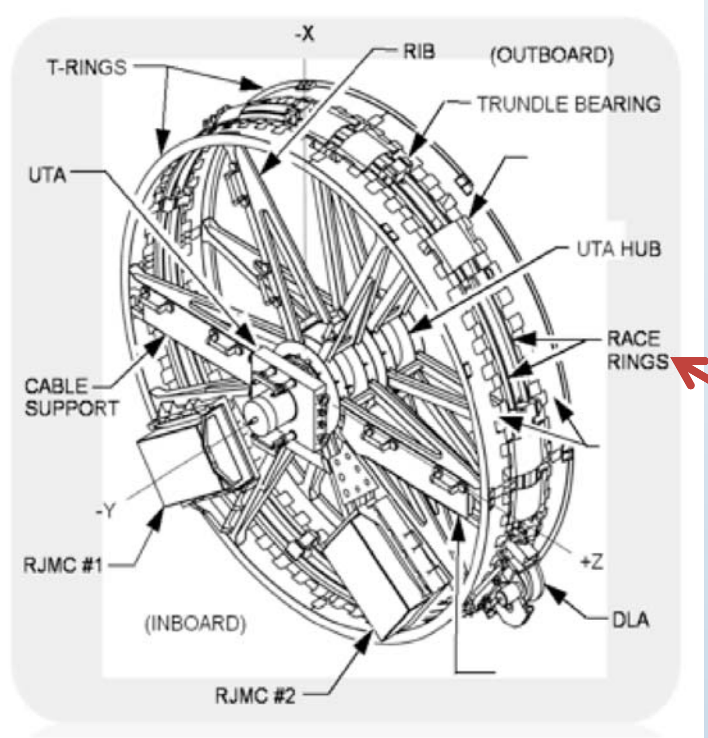




SARJ Hardware

- **SARJs:**
  - **Design sounds simple but is truly complex.**

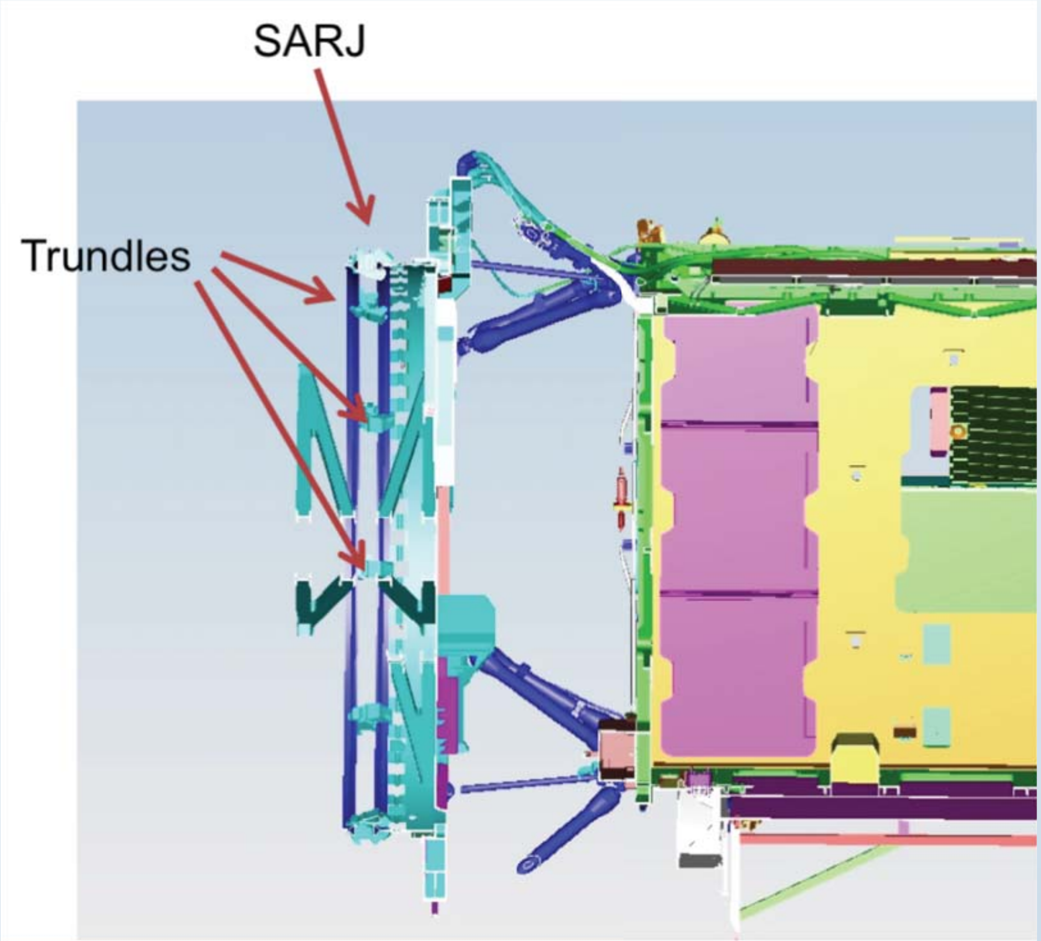




"Hula Hoops" are really called Race Rings and are joined to each other by a dozen arms called trundles.

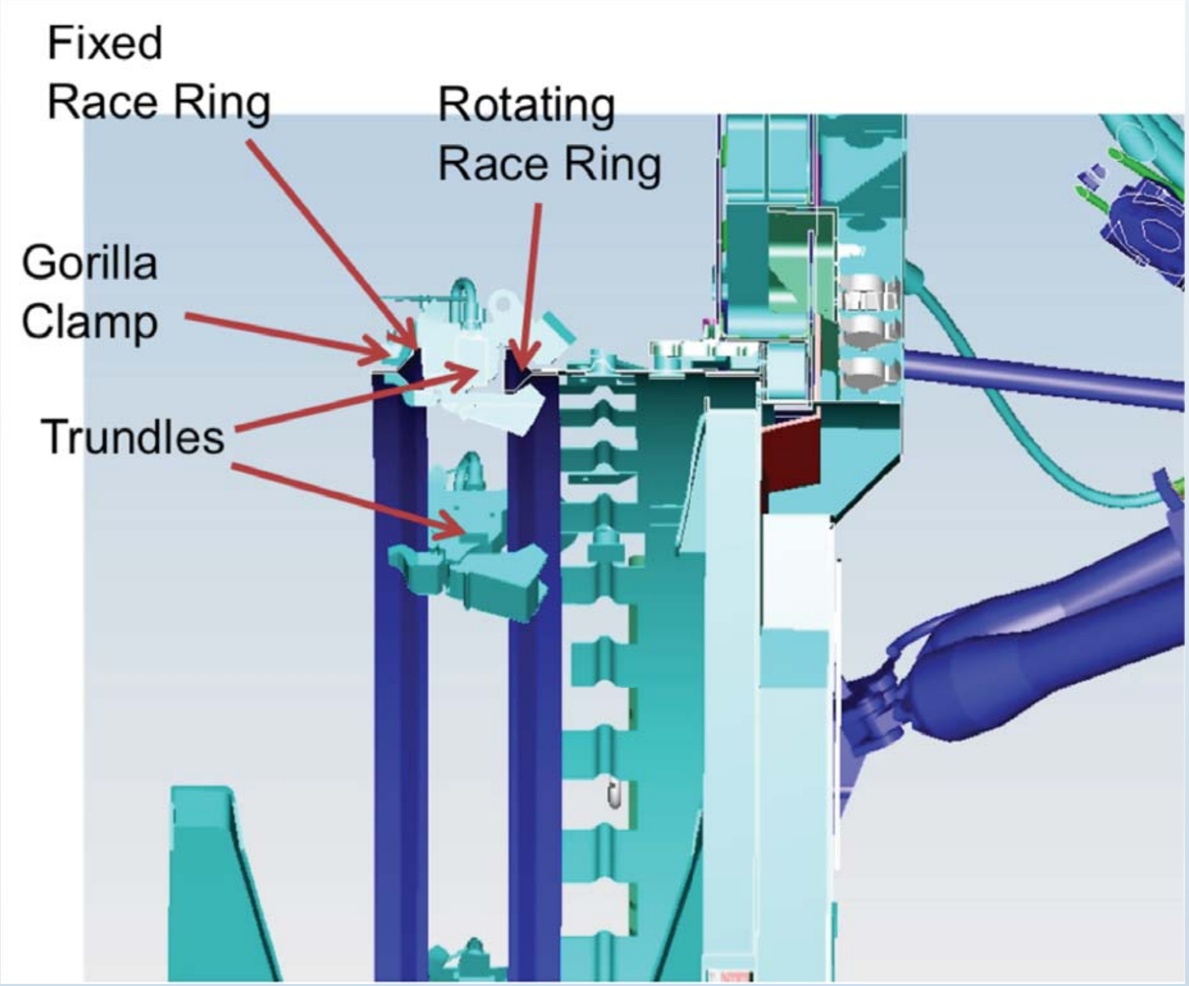
SARJ Hardware

- **SARJ Skeleton:**
  - **Animated graphic (courtesy CSA) shows the race rings and trundle arms clearly.**



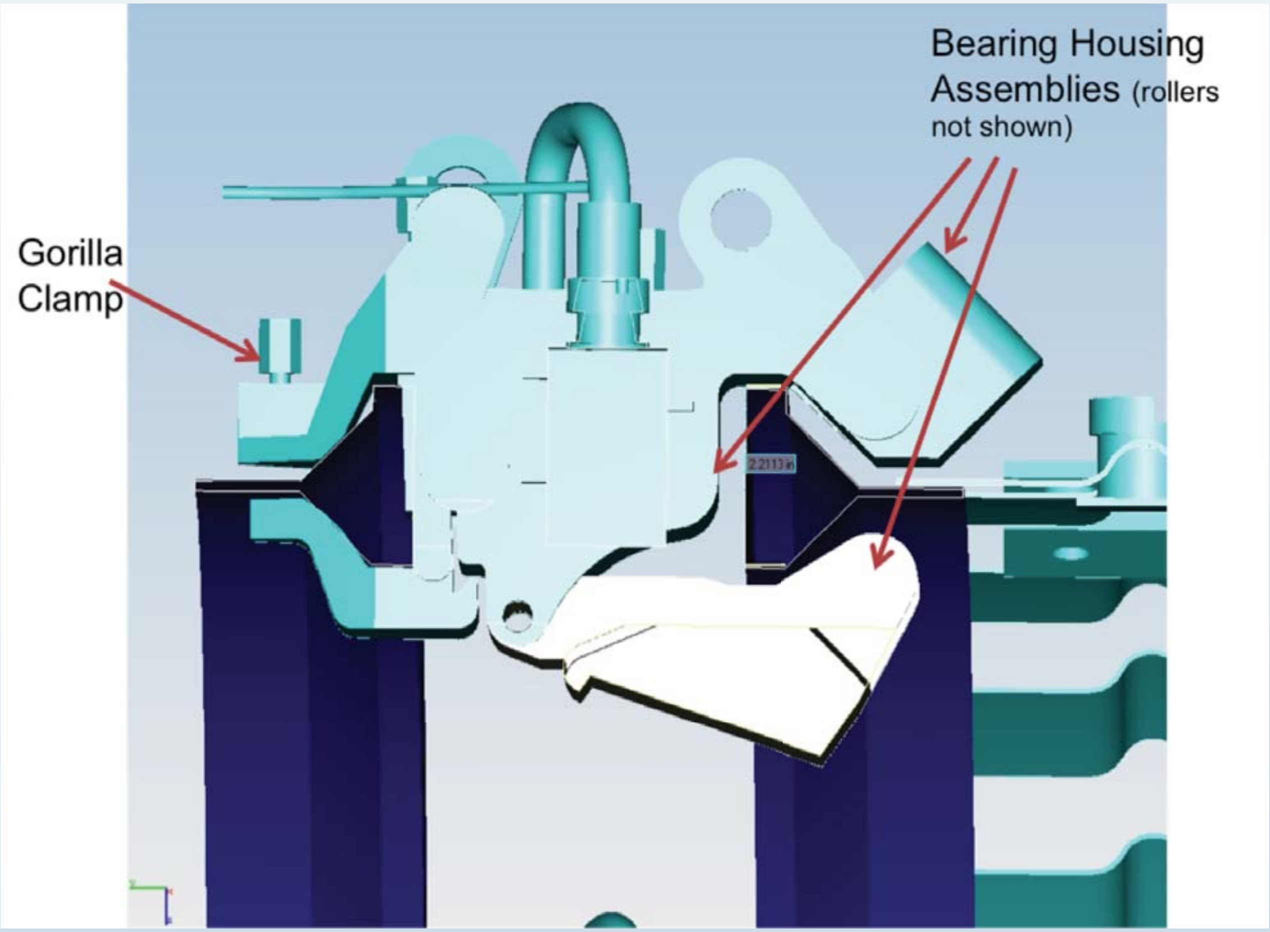
SARJ Basic Operation

- One ring stays fixed and serves as clamp surface for trundle arms.
- The other race ring freely rotates through rollers found on the other end of the trundle arms.



SARJ Basic Operation

- In truth, the race rings differ from hula hoops.
- They are nitride treated hardened stainless steel, not plastic.
- They have a triangular cross section upon which the trundle rollers ride.



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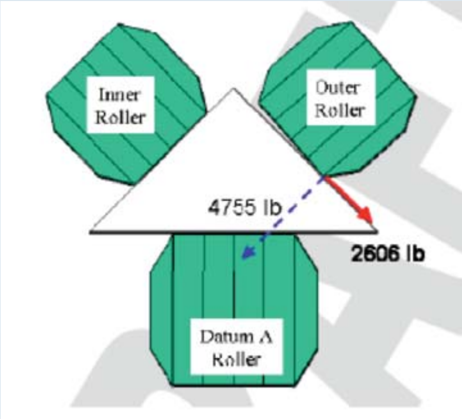
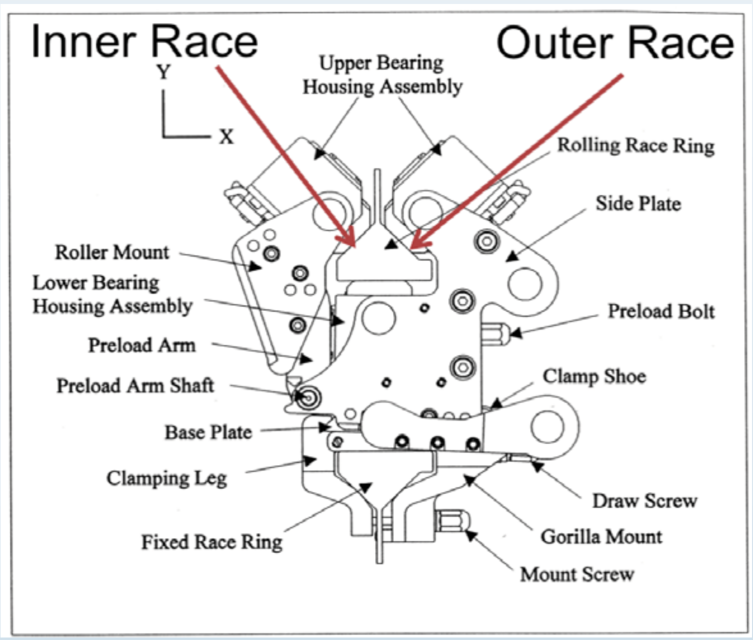


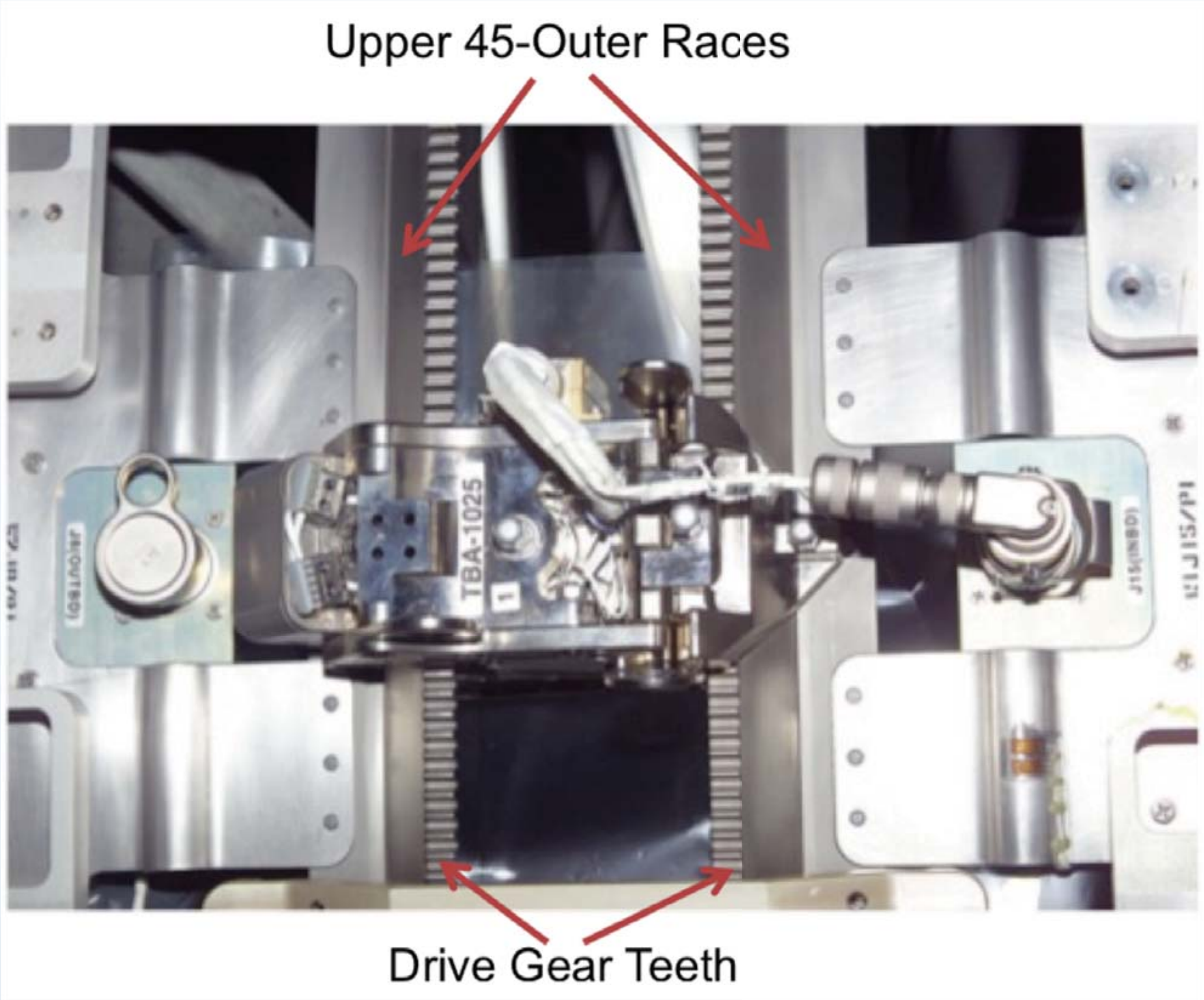
SARJ Basic Operation

- The trundle arms are the most complex SARJ component.
- The clamp ensures exacting alignment.
- The rollers and swivel housings accommodate thermal distortions, maintain preload and ensure free motion of moving race ring.



Trundle Arm "as-installed"

- Clamped to right side race ring.
- Roller housings "nestle" moving race ring on left.



Identified Failure Modes: (Mitigation approaches)

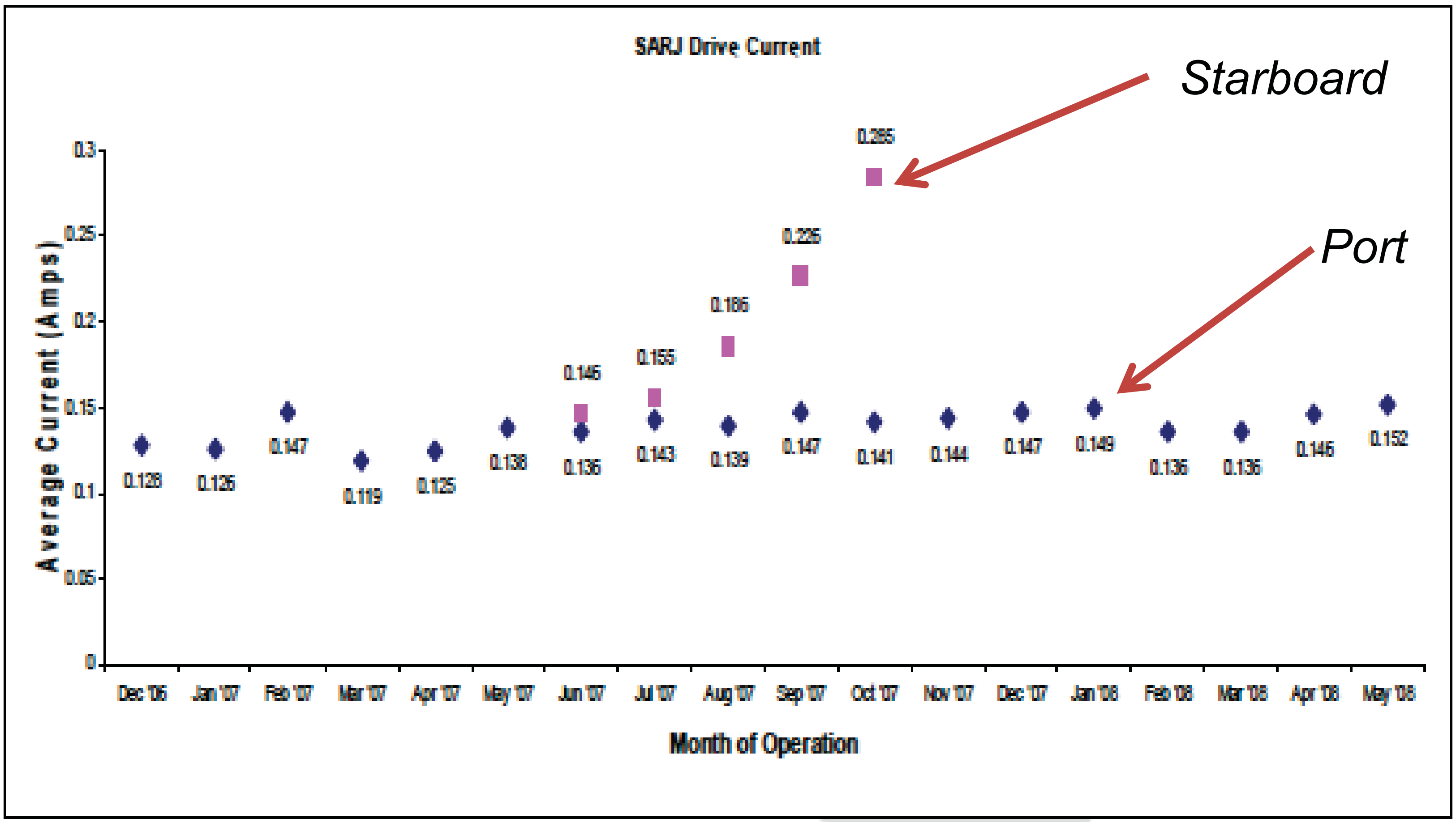
- Rolling contact fatigue spalling (pitting) of rollers and race rings
  - Super-hard, long life materials (300+ year fatigue life)
- Seizure of bearings located inside each roller
  - Back-up bushings and rotation indicators
- Atomic oxygen-radiation degradation
  - Insulation blankets
- Micrometeorite strikes
  - Shielding critical areas
- FOD jams and interferences
  - Controlled assembly to minimize potential
- Drive gear wear
  - Accelerated life test conducted
- Drive motor failure
  - Redundant drives provided.

Operational History: (Build Timeline)

- Structural Test Article: STA (very first SARJ) built in 1995
  - Proved out design, verified operation and endured gear life test
  - Tested in air, not vacuum
  - Performance matched models
- Port SARJ build followed STA using same design
  - Tested in air and vacuum in abbreviated test program
  - Behavior matched STA.
- Starboard SARJ built last using same design as port and STA
  - Tested only in air
  - Exhibited 30% higher drag torque than port and STA
  - Drag was “out of family” but well within margins

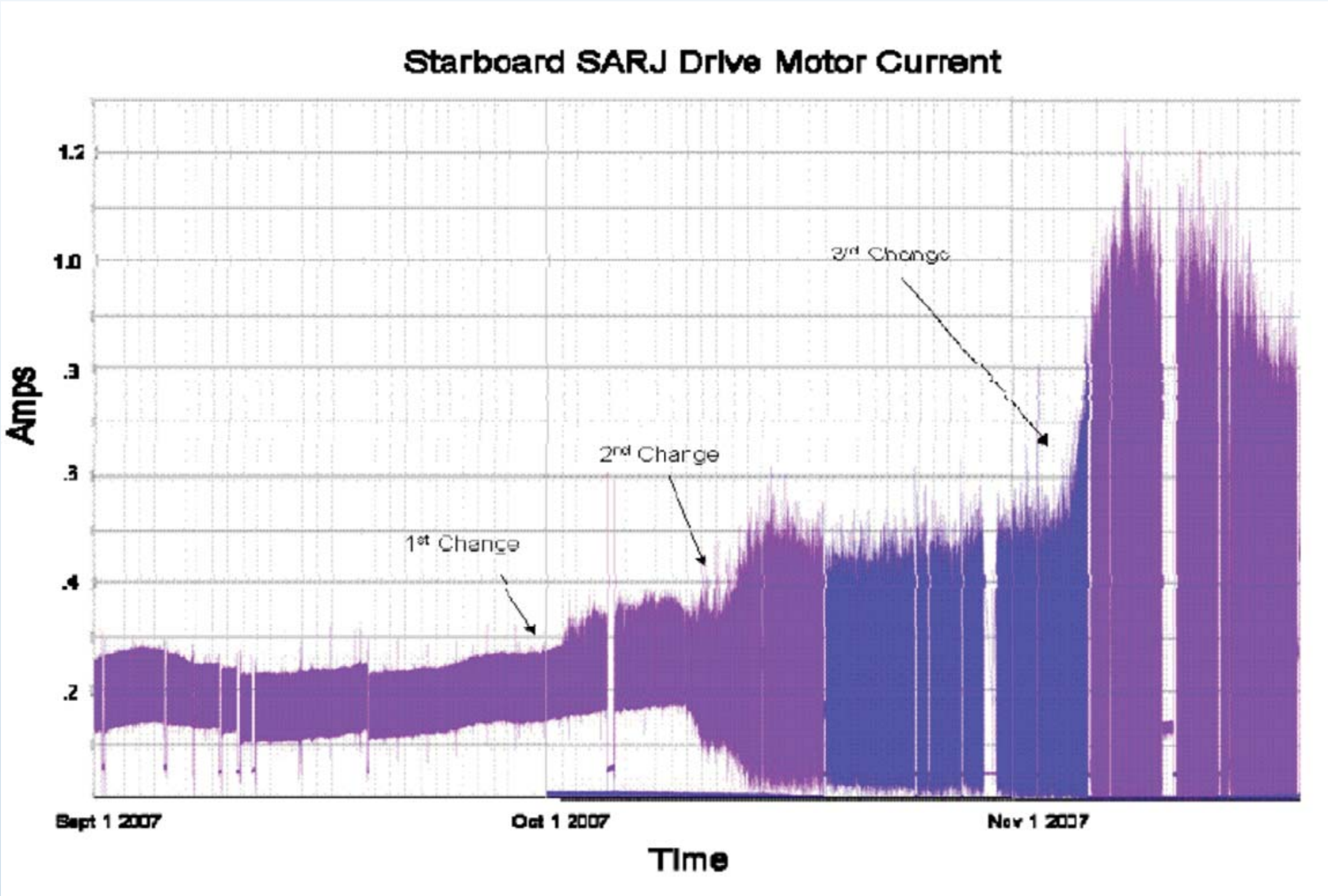
Operational History: (What Happened?)

- Port launched, installed and began rolling in December 2006.
- Starboard SARJ launched, installed and began rolling in June 2007.
  - By July 2007 drag torque began to rise.



Operational History: (What Happened?)

- By October 2007 torque levels and noise became alarming.
- In November 2007 the starboard SARJ was shut down.

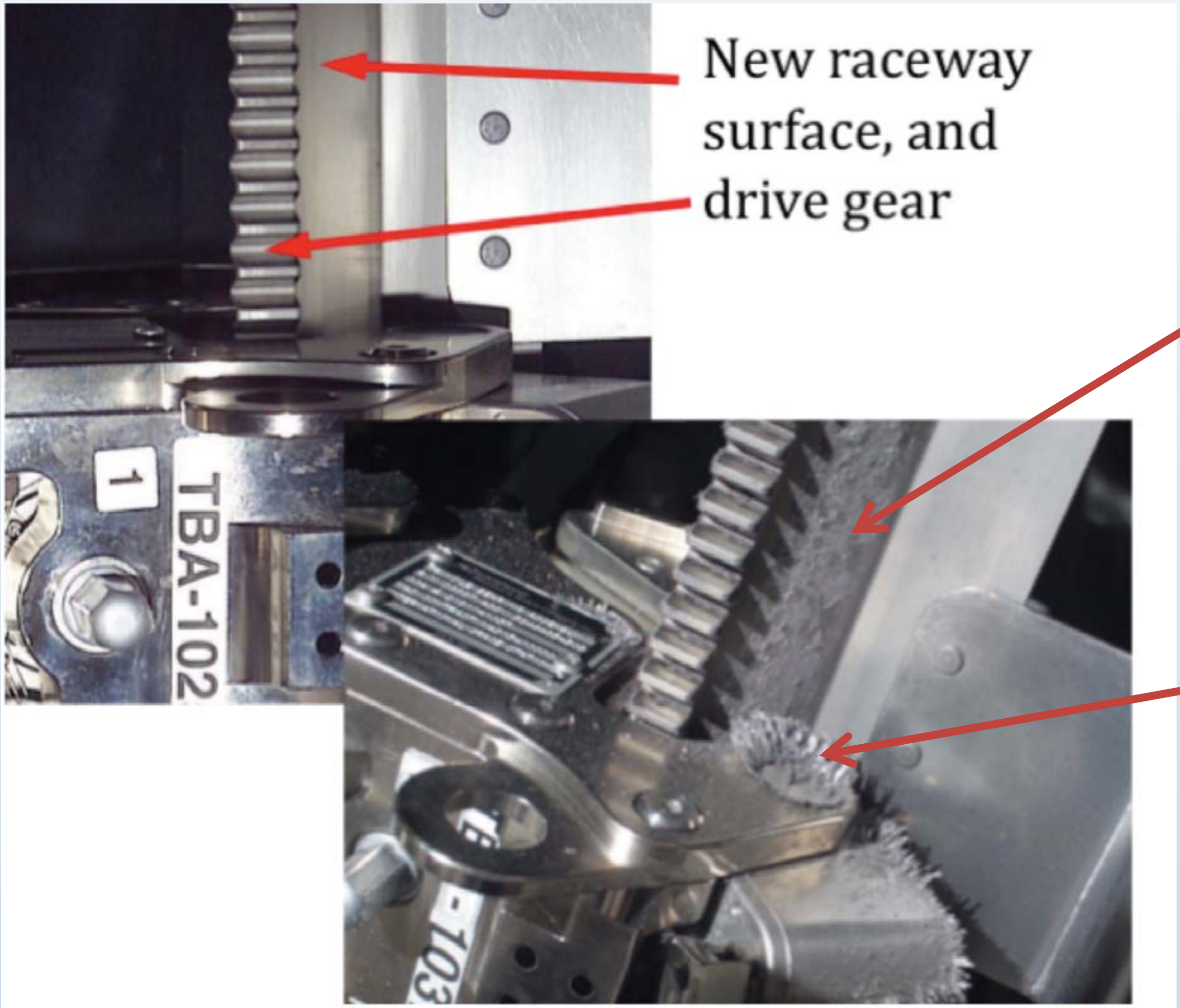


Operational History: (What was response?)

- Station managers tried to narrow down possible problems
  - Eliminated thermal effects and software problems
  - Cursory review of pre-launch images looking for obvious interference
- Approved EVA to conduct visual inspection
  - No visual damage observed on and around SARJ.
  - Astronauts given go ahead to remove one cover panel to “peek inside”.
  - What they found was not pretty.

Operational History: (What they found)

- Damage found on one (outer canted 45 race surface) surface.
  - Wear debris was everywhere…samples collected.



Race ring surface severely cratered

Shards of wear particles magnetically attached to roller housings

EVA Impact: (What we now understood)

- Drive gear teeth looked fine.
- No interference from adjacent SARJ parts.
- Nothing found that shouldn't have been there (no loose nuts, bolts, etc.)
- Damage uniformly spread over single entire race surface.
- Nitride layer on race surface bore brunt of damage.
- No scoring or drag marks, all rollers still rolling.
- No foreign matter (other than SARJ component wear particles) observed.
- No localized initiation site found (micrometeorite strike).

Root Cause Data Search Strategy

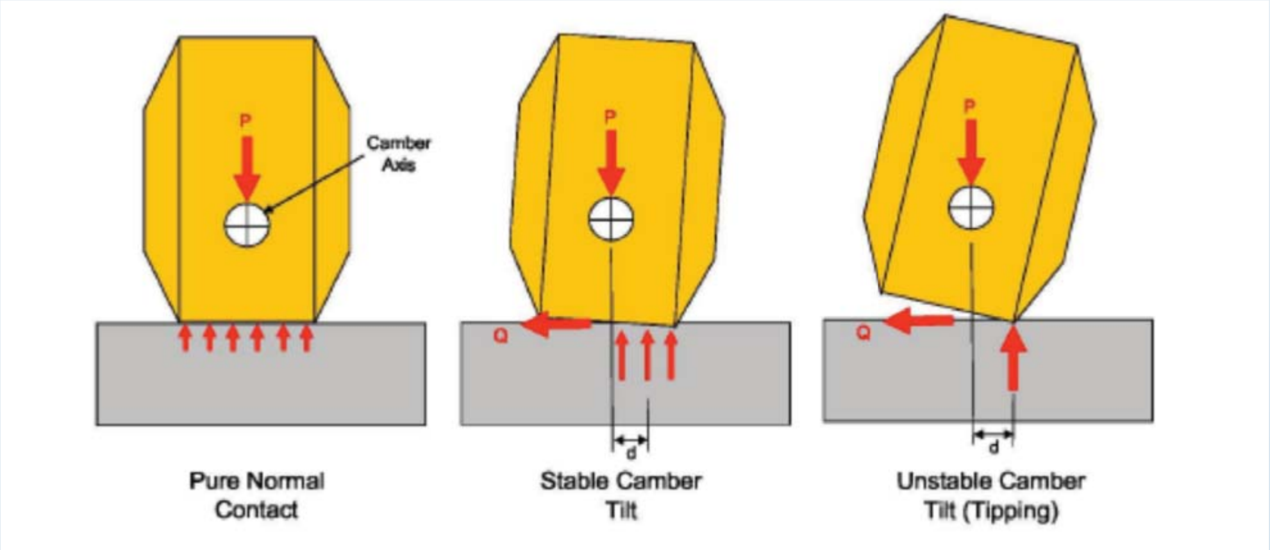
- Lacking a quick and obvious answer, an investment was then made to study working port SARJ to understand why it worked starboard SARJ did not.
  - EVA to inspect port SARJ.
  - Forensic records review extended to port SARJ
  - Key differences identified and used to formulate possible failure scenario.
  - Failure scenario verified through analysis <u>and</u> test.

Root Cause Trundle Modeling

- Roller motions, loads and stresses modeled to better understand roller-race interactions.
  - Sophisticated ADAMS modeling
  - Yielded contact stresses within rollers, races and support structures.
  - Peculiar and unexpected behavior uncovered.

Root Cause Trundle Modeling

- **Modeling suggested that under certain conditions rollers can tip on edge.**
  - **Requires some misalignment**
  - **Requires friction coefficient above ~0.4.**



•*Tipping concentrates the load onto small area leading to very high stresses*

Root Cause Evidence

- **Gold plating on starboard SARJ rollers didn't stick:**
  - **Plating met specifications when made, peeled later.**

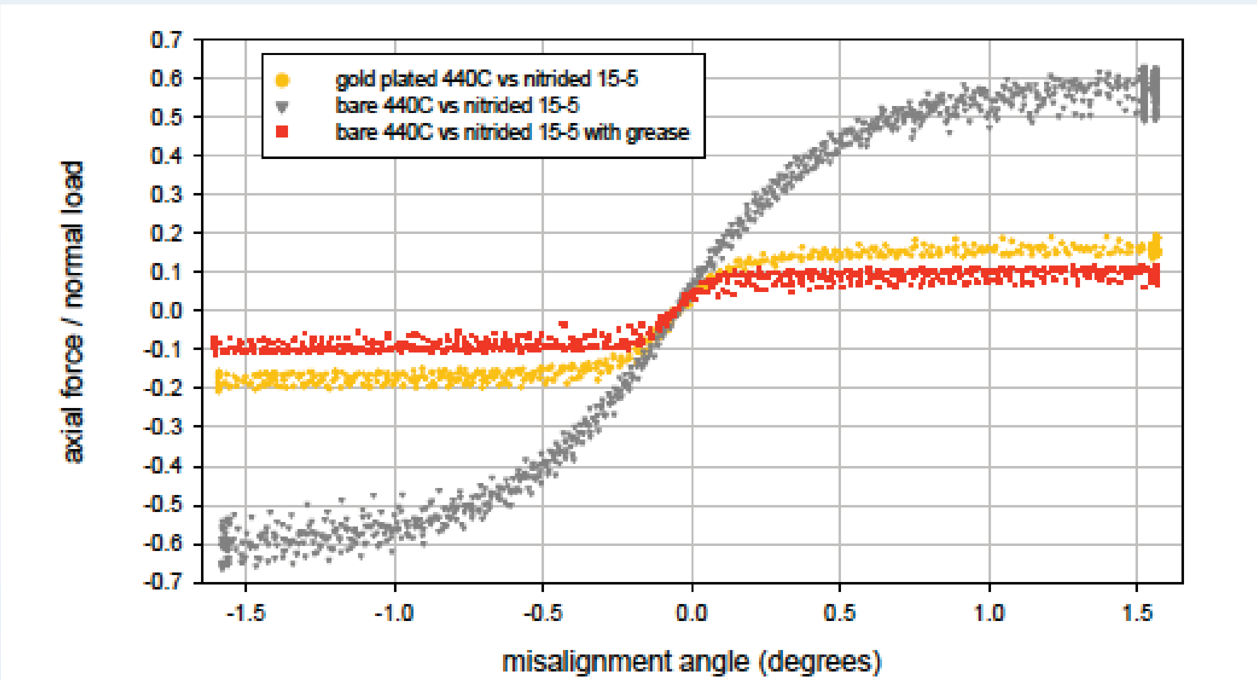
Port SARJ Roller

Starboard SARJ Roller

**Note: Process used for plating identical. Major difference was port rollers used immediately after plating, Starboard rollers stored for months before use.*

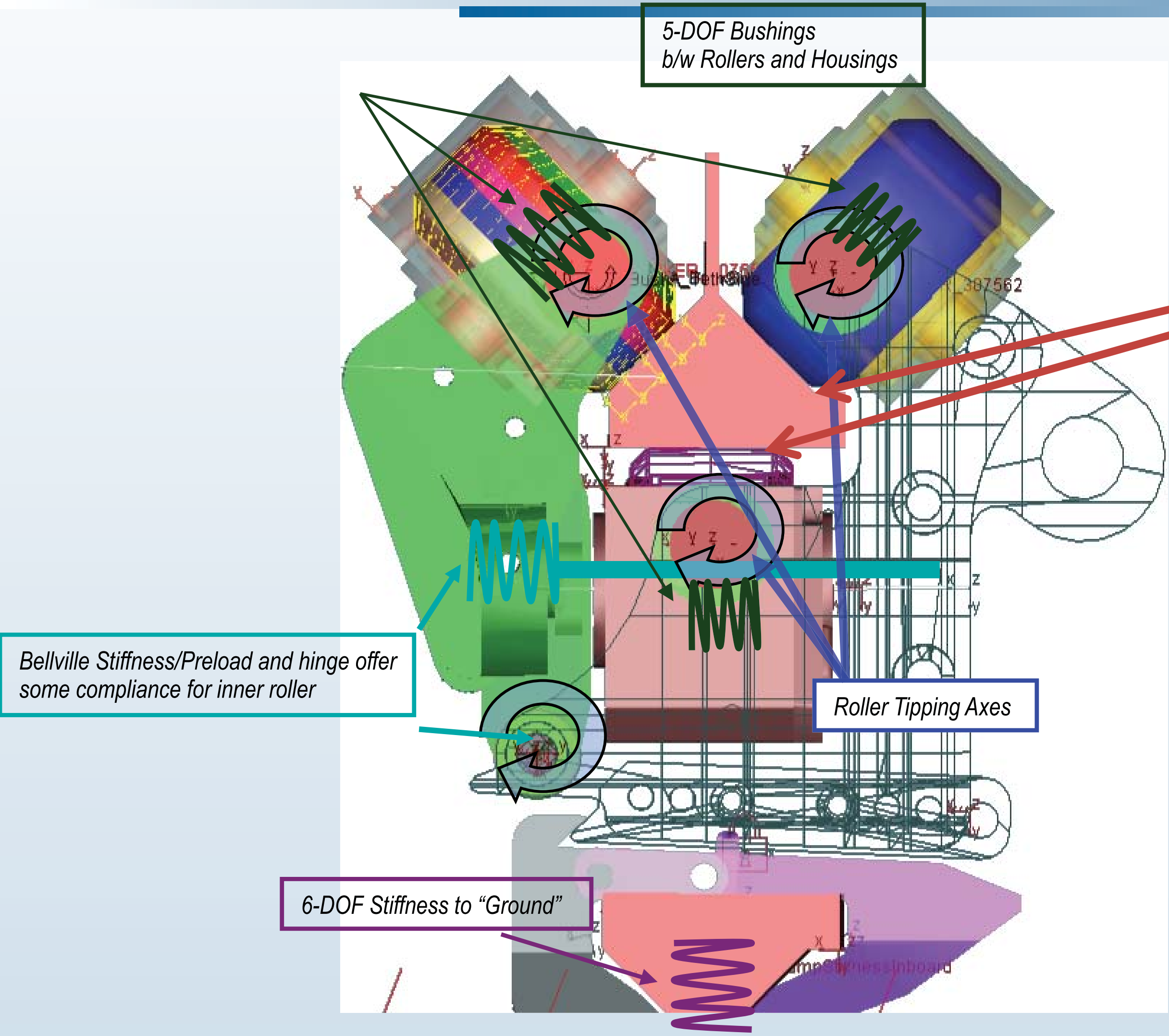
Validation data for modeling

- **Testing measured friction for rollers:**
  - **In vacuum using SARJ materials**
  - **With gold, w/o gold and with grease.**



•*Intact gold and grease both yield low friction. Rollers with no lubrication give friction well above 0.4.*

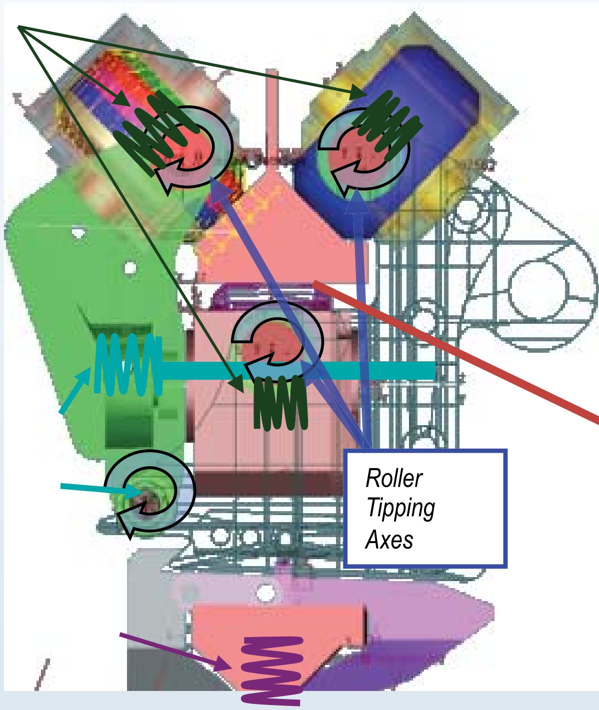
Roller Miss-Tracking-Tipping Effects



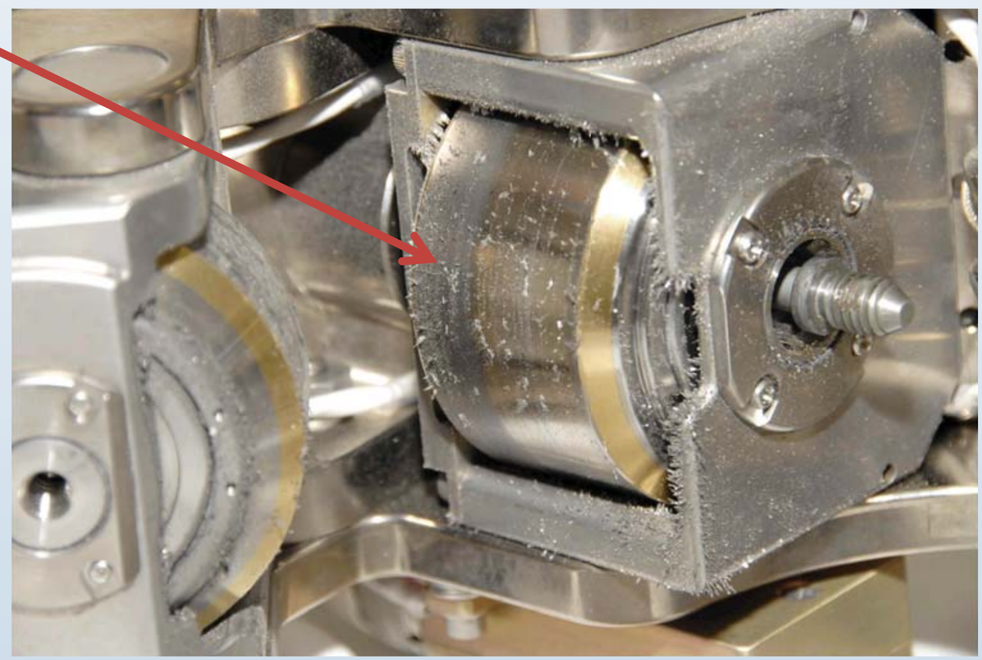
Most vulnerable race ring pinch points.

- *Should two rollers tip towards each other, the race can be pinched causing loads and stresses to soar.*

Roller Tipping Confirmed



Inspection of hardware returned from orbit confirmed roller tipping.



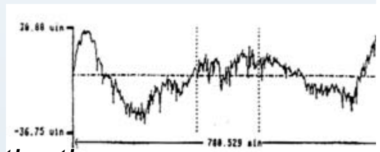
•*Careful wear measurements eventually done on all twelve trundles proved that rollers indeed behave in the peculiar tipping-pinching fashion predicted by model.*

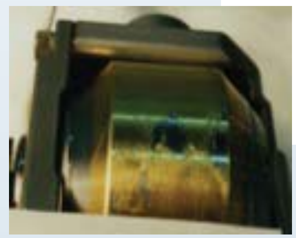
Root Cause Failure Scenario: the "how"

Inadequate lubrication of the roller-race contact, combined with a kinematic mechanism design that is vulnerable to roller tipping and high friction, led to damaging high roller-race surface forces and stresses.

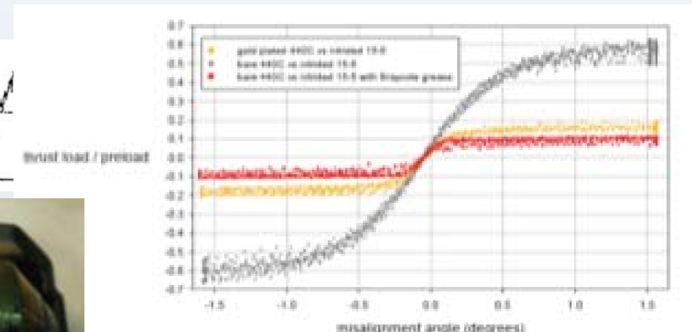
Problem

Investigation



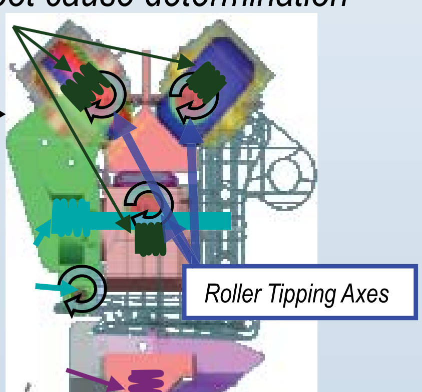


Design analyses and records search



Tribology test data and expertise

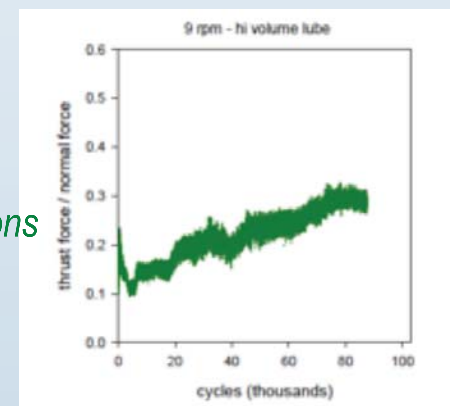
Root cause determination



Understanding

T. Krantz and C. DellaCorte (RXN)

Recovery-Operations



Lube life testing: ongoing

SARJ Epilogue: Recovery Planned

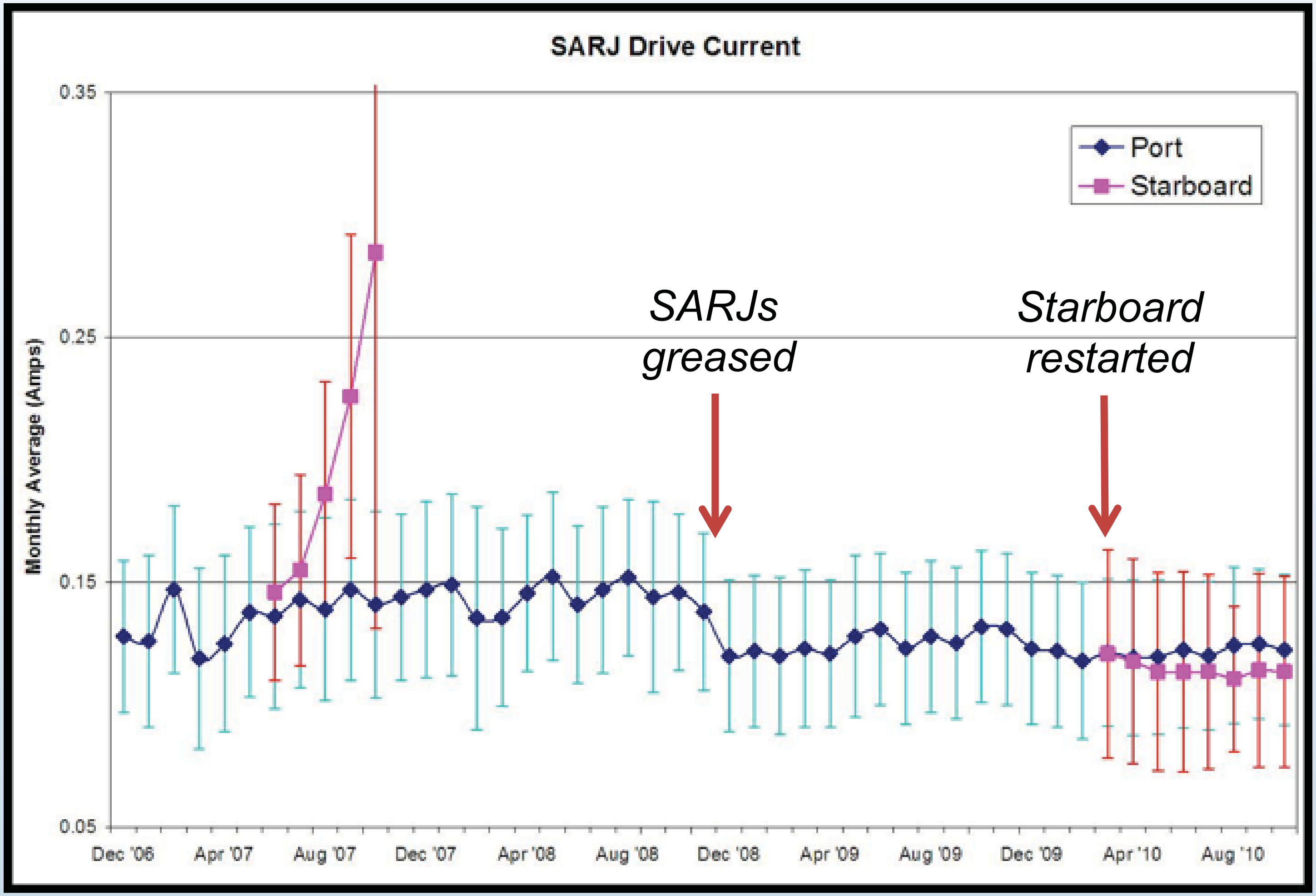
- Ground tests <u>and</u> analyses showed that grease ensures low friction was an appropriate recovery path.
  - STS-126 trained for SARJ repair and recovery.

SARJ Epilogue: A truly happy ending

- **EVA's in November 2008 to replace worn trundles, remove debris and grease starboard SARJ.**

Operational History: ("Current" Status)

- Both SARJs were greased in November 2008.
- Port SARJ torque dropped 20%.
- Starboard SARJ rotation began in 2010 following verification ground tests



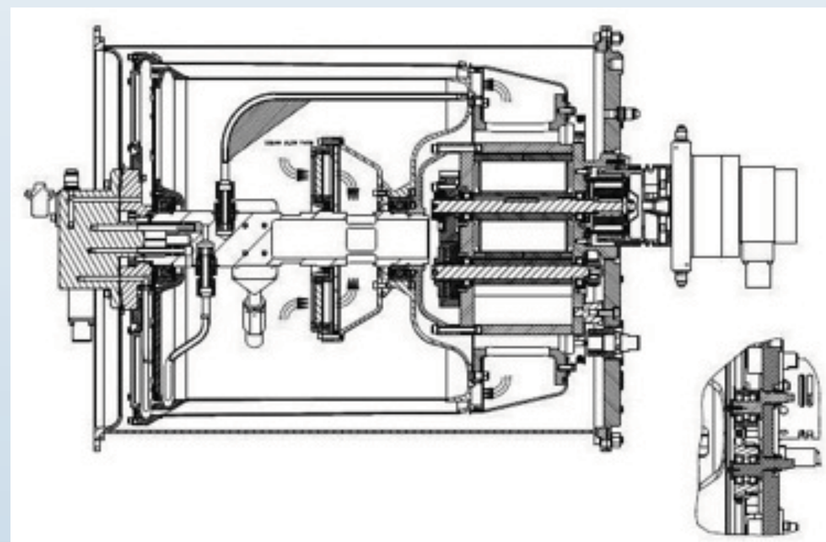
SARJ Epilogue: A truly happy ending, 5+yr

- Current draw for the Starboard SARJ is a bit noisier than the Port SARJ, it continues to function well within limits and is getting smoother.
  - Ground tests suggest that re-lube interval is measured in years.
  - The ISS power system is fully functional.

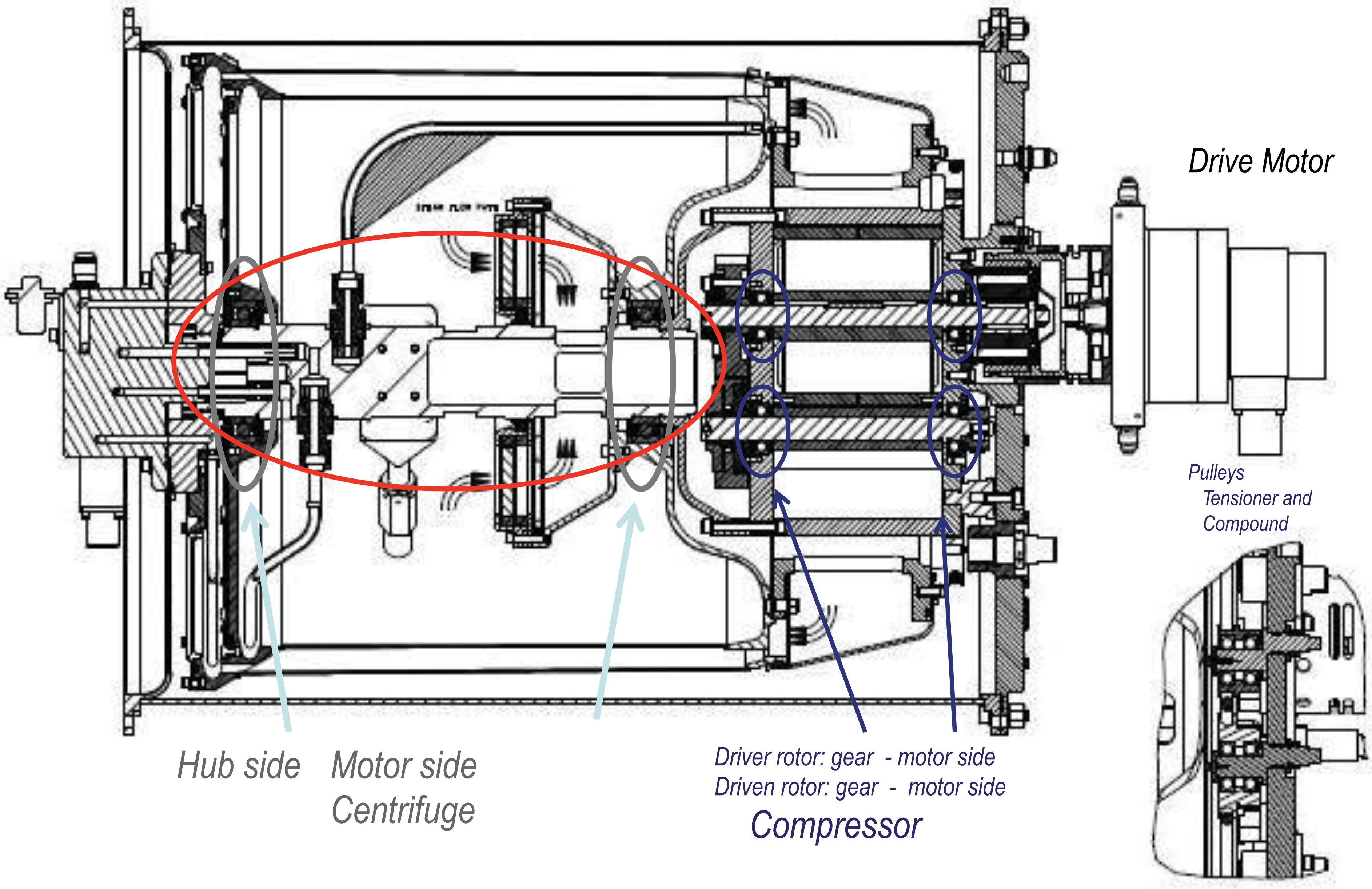
ISS: Tribology Challenge Examples

- SARJ Bearing Failure:
  - In space environment outside.
  - Continuous slow rotation
  - Vital to ISS operation. Failure not an option.

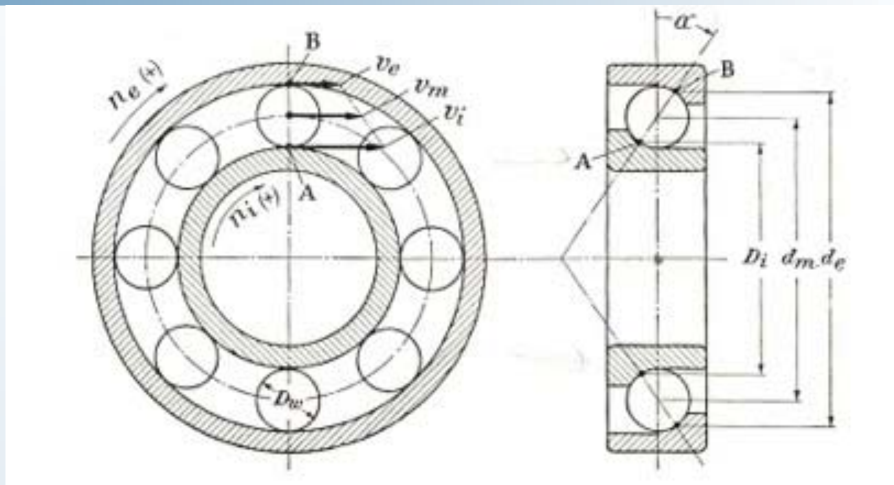
- ECLSS Distillation Assembly:
  - Inside ISS, warm, wet, corrosive environment.
  - Intermittent use.
  - Changes/trials possible.



Superalloy Centrifuge Bearings Wear



Technical Requirements:
(Material properties needed for bearings/components)



- **Bearing and component materials must be:**
  - 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 centripetal loads at high rpm)
  - Capable of producing ultra-smooth surface finishes
  - Dimensionally stable and easy to manufacture

Technical Challenge:

(Current suite of candidates is severely limited)

- Four general types of bearing and tribo-mechanical materials:
  - Steels (Corrosion resistant steels, martensitic, austenitic)
  - Ceramics (Si_3N_4 hybrid bearings)
  - Superalloys
  - 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 are non-conductive (and operate on steel raceways)
  - 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.

Technical Opportunity:
60NiTi (a.k.a. NiTiNOL 60)

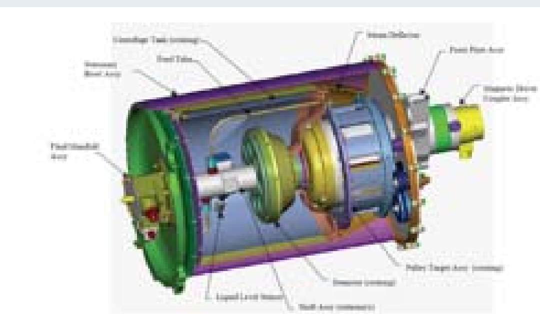
- **60NiTi Basics:**
  - Invented by W.J. Buehler (late 1950's) at the Naval Ordinance Laboratory (NiTiNOL stands for Nickel-Titanium Naval Ordinance Lab).
  - Contains 60 wt% Nickel and 40 wt% Titanium
  - 60NiTi is neither a metal nor a ceramic: a weakly ordered inter-metallic compound; a member of the super-elastic family.
  - Its cousin (55NiTi), the widely used shape memory alloy, is soft and dimensionally unstable.
  - The additional Ni suppresses the shape memory affect. 60NiTi is dimensionally stable.
  - 60NiTi can be hardened to Rc 60+.
  - 60NiTi recognized by Buehler for bearings but too difficult to manufacture using 1960's technology.
  - Modern (ceramic) processing methods now enable 60NiTi bearings with remarkable, breakthrough properties. (Patents awarded to protect IP).

60NiTi Target Application: ISS Urine Processor Distillation Assembly Bearings

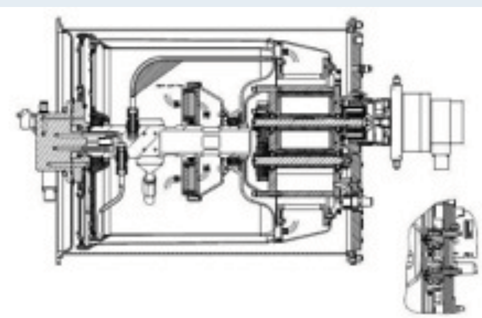
***Problem**: Bearings in the ISS urine processor utilize soft superalloy races and hard ceramic balls to withstand the corrosive environment but are prone to wear and damage from assembly and shock loads.*

***Approach**: Review design and engineer a corrosion proof, shock proof 60NiTi bearing that, once proven, could be a drop-in replacement.*

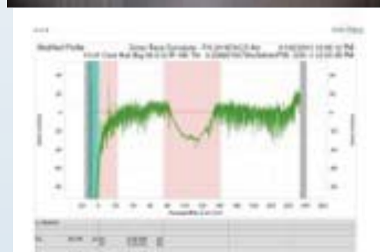
Distillation Assembly



DA Schematic



Centrifuge bearing races



Unit #2 raceway wear

Status: Team assembled. Baseline bearing designed, manufactured and tested in simulated environment. Flight bearing manufacture underway.

Expected Payoffs: Successful use of 60NiTi bearings on ISS will ease transfer of such technology to future terrestrial and space applications.

Centrifuge Bearing Components

50 mm Bore

Disassembled Components

Inner Ring

- *Soft (Rc 40) superalloy races used in centrifuge location for corrosion resistance*
- *Si_3N_4 Balls with nylon snap fit cage and grease shields*

DA Centrifuge Bearing Requirements*

Parameter	Value
OD	75mm
ID	50mm
Width	16mm
Ball Size	8.6mm
Ball Compliment	13 balls
Ball Material	Si_3N_4
Race Material	Superalloy
Cage	Snap fit, polymer
Lubricant	grease
Ball-Race Stress Limit	240 Ksi
Ball-Race Mean Stress	120 Ksi
Axial Preload	40 lbs
Radial Load (terrestrial)	~30 lbs/bearing
Speed	220 rpm
Environment	65°C, acidic aqueous splash
Ambient Pressure	~8 Psia

Centrifuge bearings are in a highly corrosive but mechanically benign environment.

Technical Properties Comparison:

Updated Thermophysical and Mechanical Properties of Bearing Materials					
Property	60NiTi	55NiTi	440C	Si_3N_4	M-50
Density	6.7 g/cc	6.5 g/cc	7.7 g/cc	3.2 g/cc	8.0 g/cc
Hardness	56-62 Rc	35-40 Rc	58-62 Rc	1300-1500Hv	60-65Rc
Thermal Cond. W/m-°K	~9-14	9	24	33	~36
Thermal Expansion	$\sim 11.2\times10^{-6}$/°C	$\sim 10\times10^{-6}$/°C	10×10^{-6}/°C	2.6×10^{-6}	$\sim 11\times10^{-6}$/°C
Magnetic	Non	Non	Magnetic	Non	Magnetic
Corrosion Resistance	Excellent (in acids)	Excellent	Marginal	Excellent	Poor
Tensile/Flexural Strength	~1000/1500MPa	~900 MPa	1900 MPa	600-1200MPa (Bend Strength)	2500 MPa
Young's Modulus	~90-115 GPa	~100 GPa	200 GPa	310 GPa	210 GPa
Poisson's Ratio	~.34	~.34	.3	.27	.30
Fracture Toughness	~20	TBD	22 MPa/√m	5-7 MPa/√m	20-23 MPa/√m
Max. Use Temp	~400°C	~400°C	~400°C	~1100°C	~400°C
Elect. Resistivity	$\sim 1.04\times10^{-6}$ Ω-m	$\sim 0.80\times10^{-6}$ Ω-m	$\sim 0.60\times10^{-6}$ Ω-m	Insulator	$\sim 0.18\times10^{-6}$ Ω-m

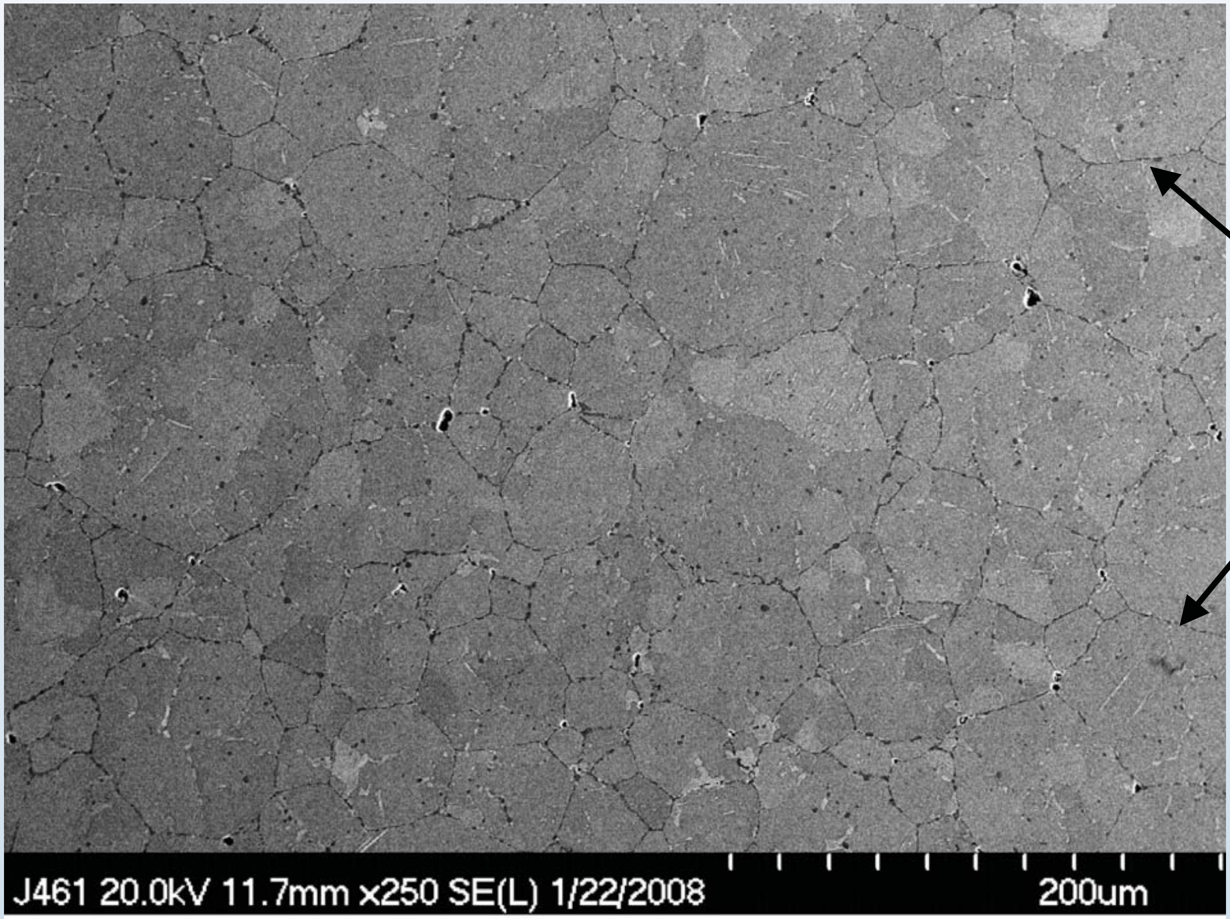
*TBD means "to be determined"

60NiTi: Grade 5 test balls

The ability to achieve required roundness and surface finish in 60NiTi is predicated upon isotropic mechanical-physical properties of the ball blank (provided by the NASA-Abbott process).

60NiTi: Ball microstructure

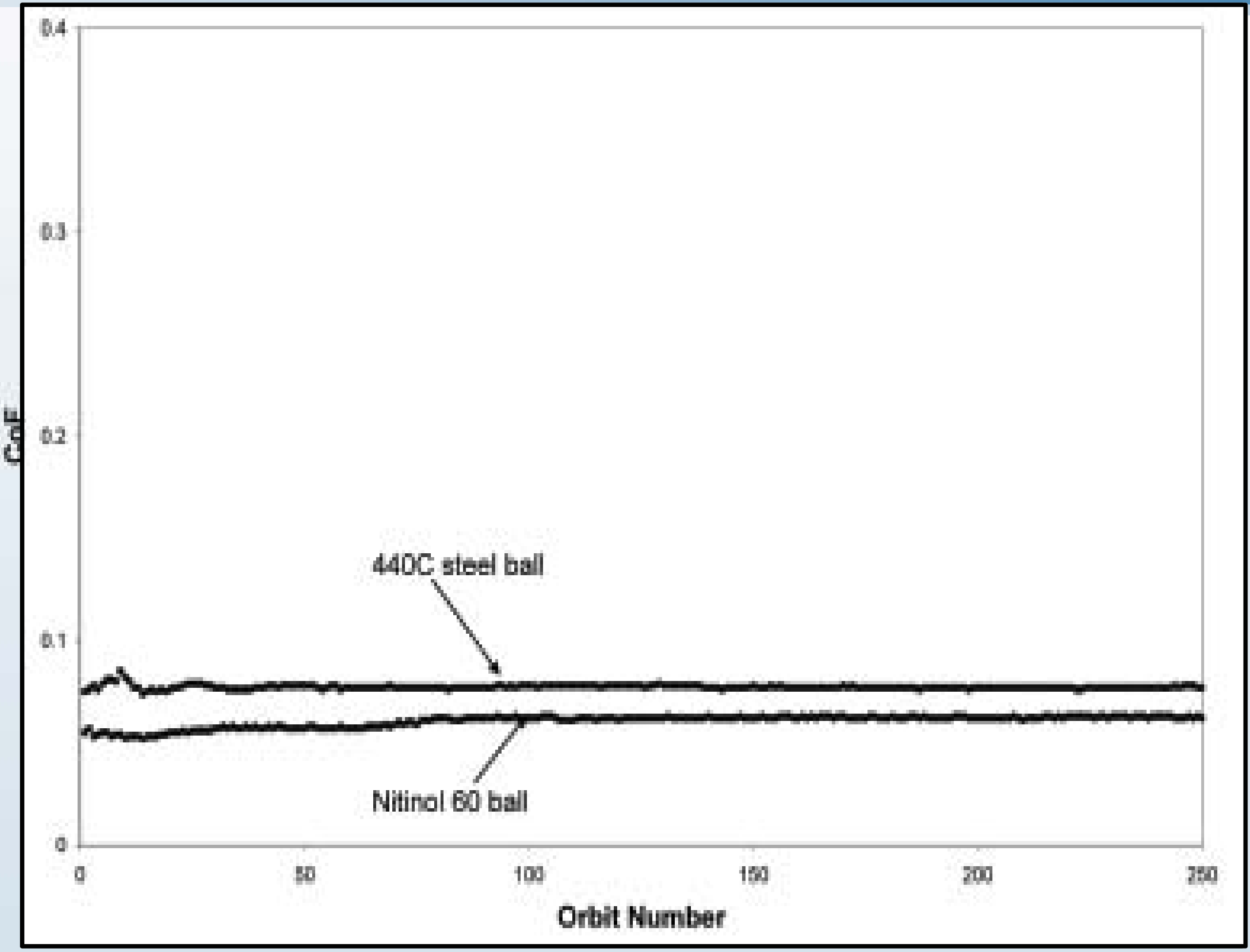
Fine grain structure typical for powder metallurgy



Original particle boundaries

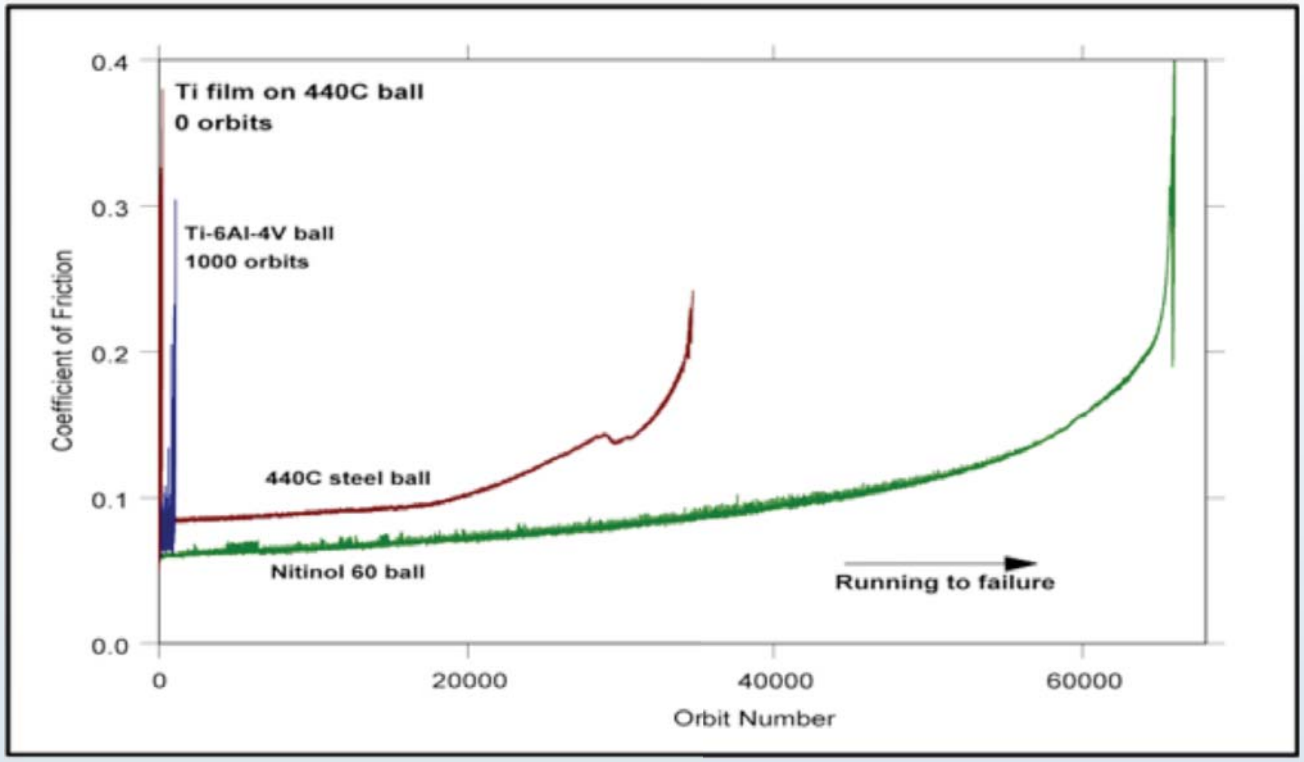
Cross section reveals small amounts of secondary phases and is typical for PM NiTi alloys.

60NiTi: SOT results comparison (beginning of test)



60NiTi exhibits slightly lower, but comparable friction to 440C. Plates were 440C in both tests.

60NiTi: Friction and lubricant life testing



- 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.
- 60NiTi is also corrosion proof, non-magnetic and electrically conductive.

Corrosion Study

Material	Weight Loss (mg)
60NiTi (pH 2)	0.11
60NiTi (pH 6.5)	0.03
Co Alloy (pH 2)	0.39
M 50 Tool Steel (pH 2)	27.6

- 60NiTi-Corrosion resistance of a superalloy.
- 60NiTi-Structural capability of tool steel.

All samples were soaked for 4.8 days at 60-65 ^{o}C

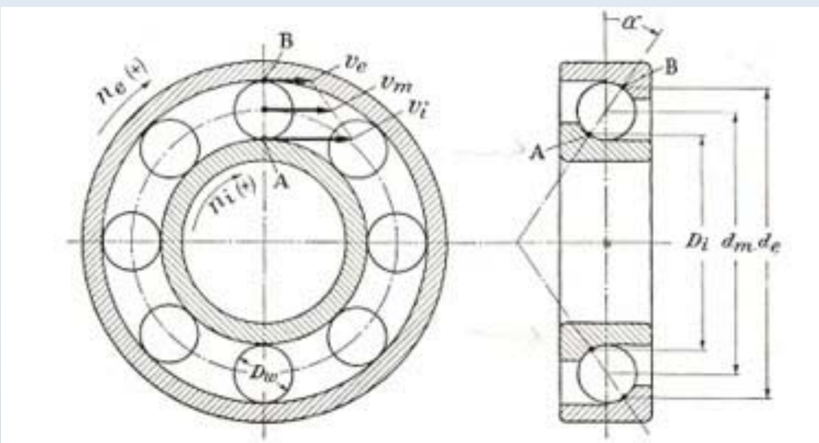
Technical Opportunity:
(60NiTi-a newly rediscovered alloy)

- **What do we now understand about 60NiTi?**
  - Favorable mechanical and physical properties that are largely independent of processing route (PM vs. casting)
  - Dimensionally stable-free from shape memory behavior
  - Excellent chemical properties (corrosion "proof")
  - Good tribological properties (despite high Ti content)
  - Electrical conductor and non-magnetic (good for sensitive instruments and electrical machines)
  - Fairly easy to manufacture into complex shapes and components (bearing balls and races, rollers, gears etc.)
  - Only alloy known to possess all of these (and other) attributes.

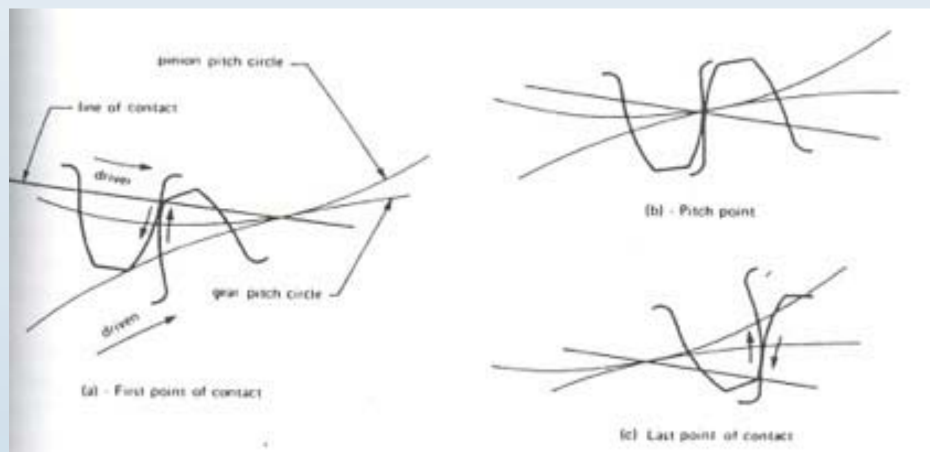
Materials Properties: Dent Resistance

- **60NiTi contact behavior is surprising and relevant:**
  - 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

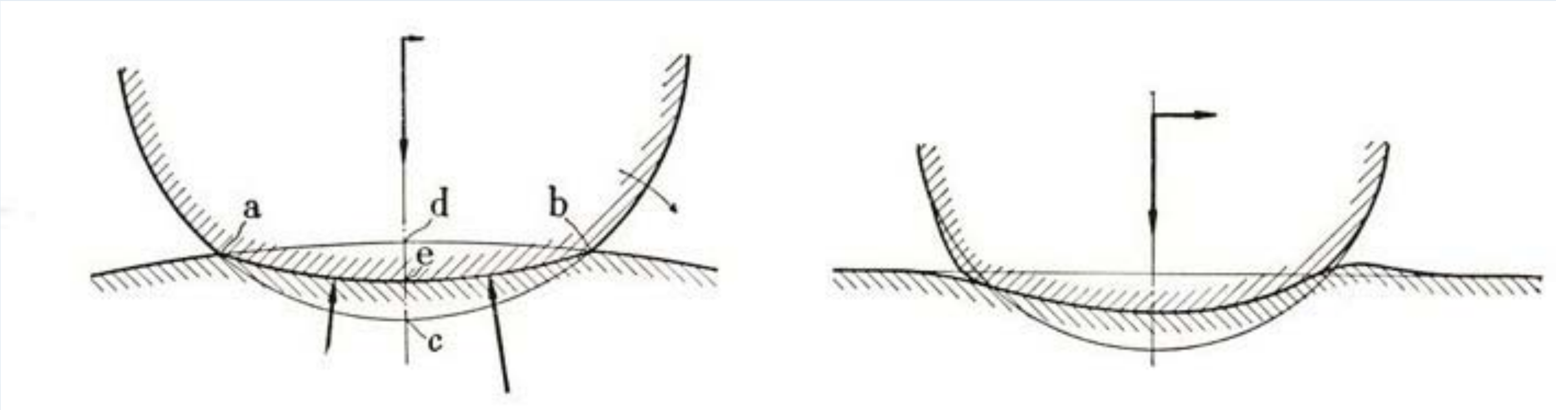


Meshing gear teeth are small line contacts



Contact Engineering:
(60NiTi's properties affect contact stresses)

- When hard surfaces contact
  - Forces are transmitted at small, concentrated contact points (Hertz).
  - Resulting stresses cause deformations that help "spread the load".
  - Contact area is a function of the geometry, material stiffness and load.
  - High stiffness (modulus) inhibits deformations leading to small contact area and high stresses (contrast with a tire contacting the ground).

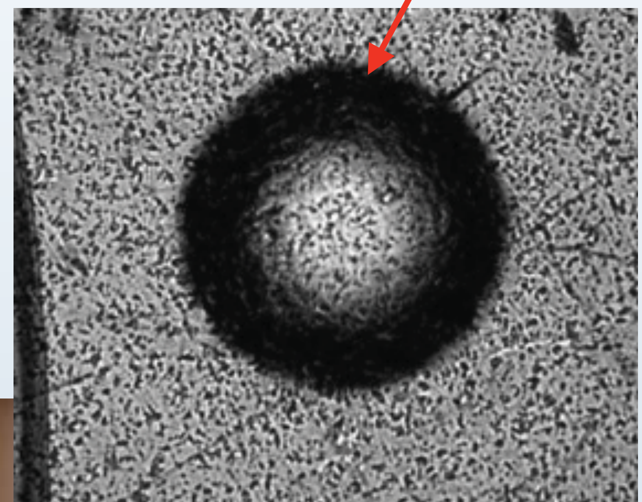


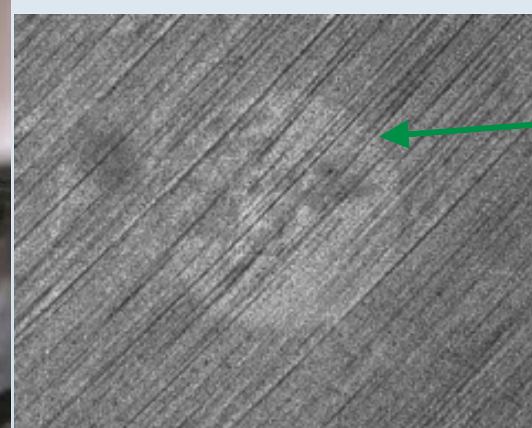
•Hertz stresses are a function of load, radii of surfaces and elastic moduli.
•When stress exceeds limit, dents occur and lead to failure.
•Mechanical designs include margins for overloads or vibe-shock isolation adding weight and expense.

Brinell Test:
(Static denting behavior)

- **How well does 60NiTi resist dents?**
  - Brinell number
  - Threshold load to damage

Deep Brinell dent.

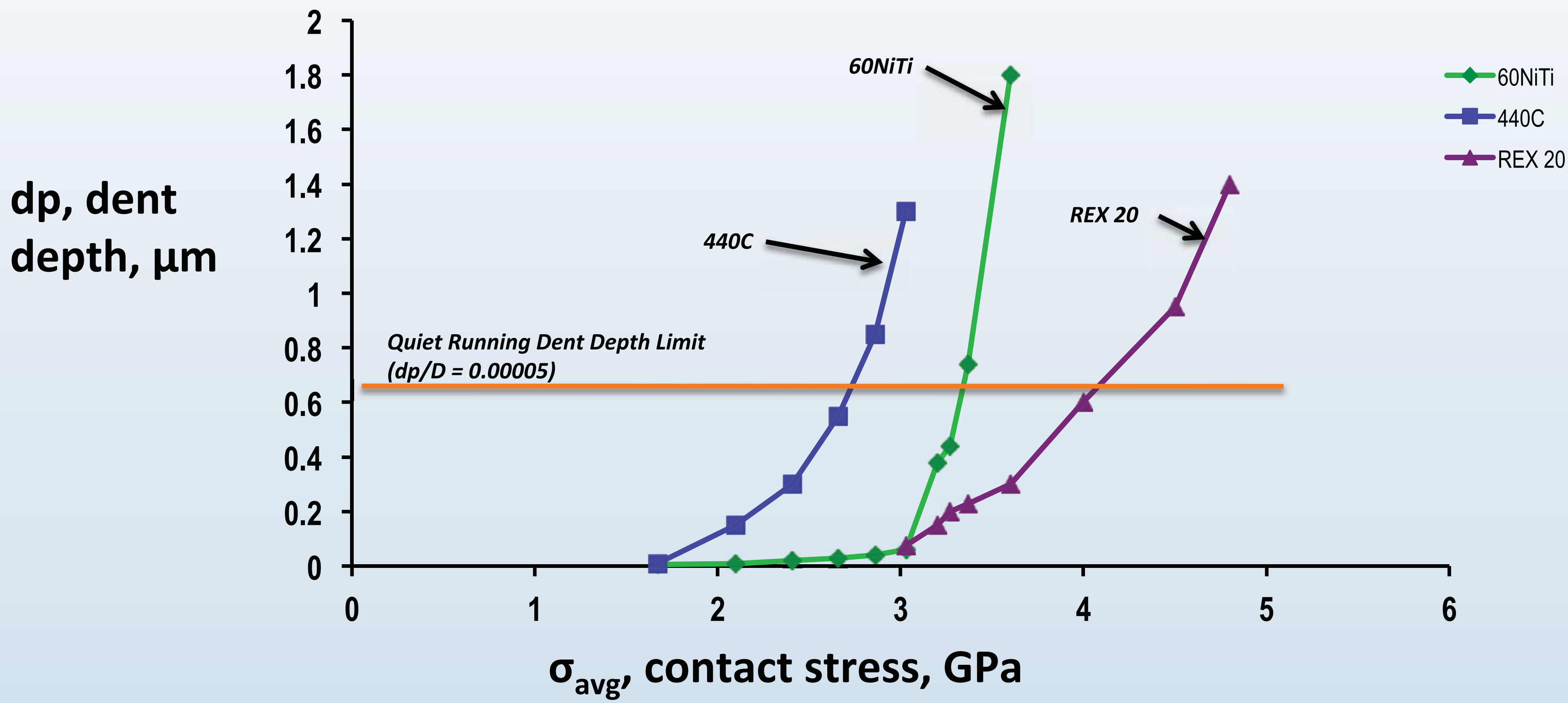




Threshold load visible dent.

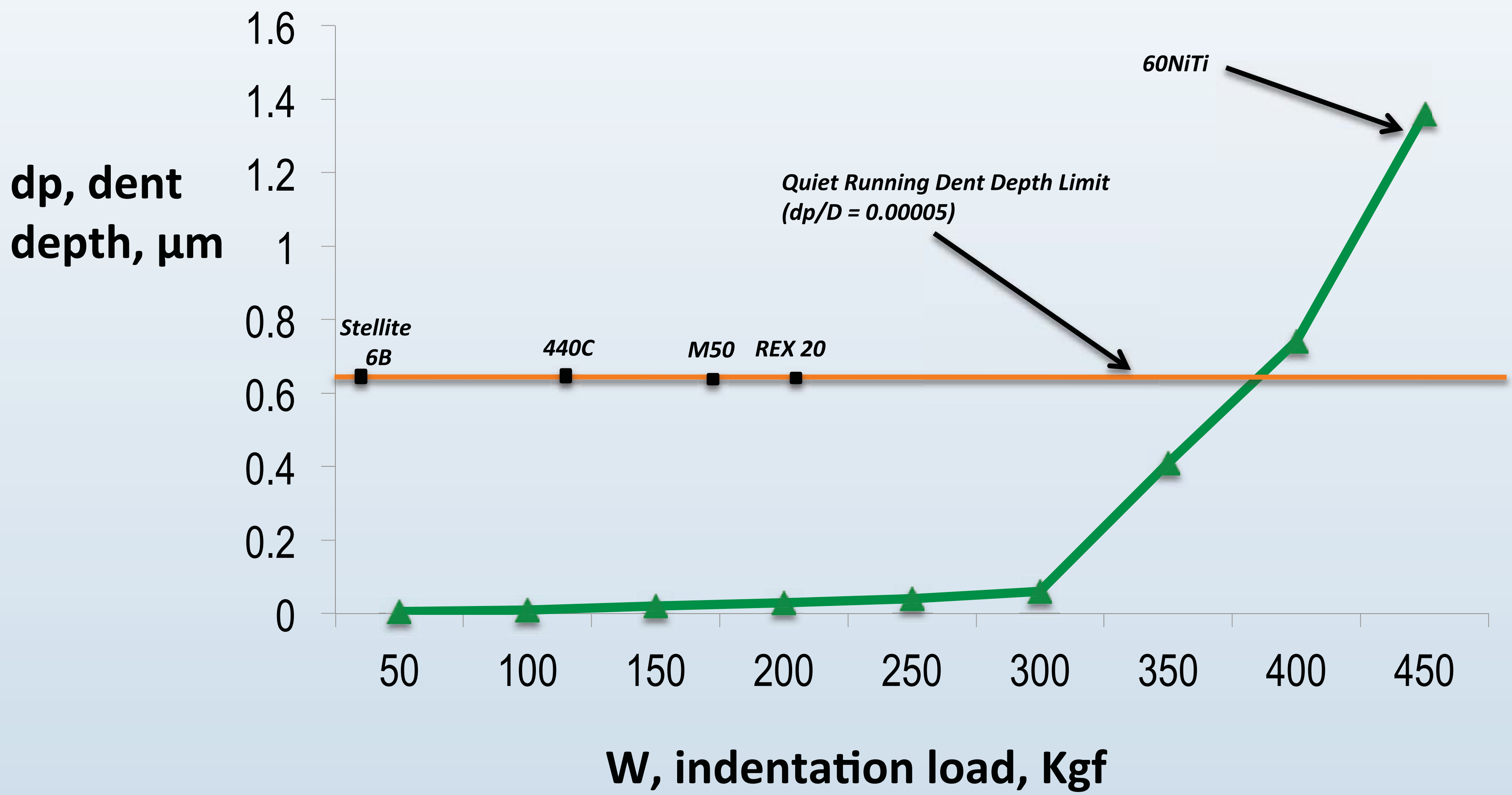
Dent Depth vs. Hertz Contact Stress

(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)



Dent Depth vs. Load

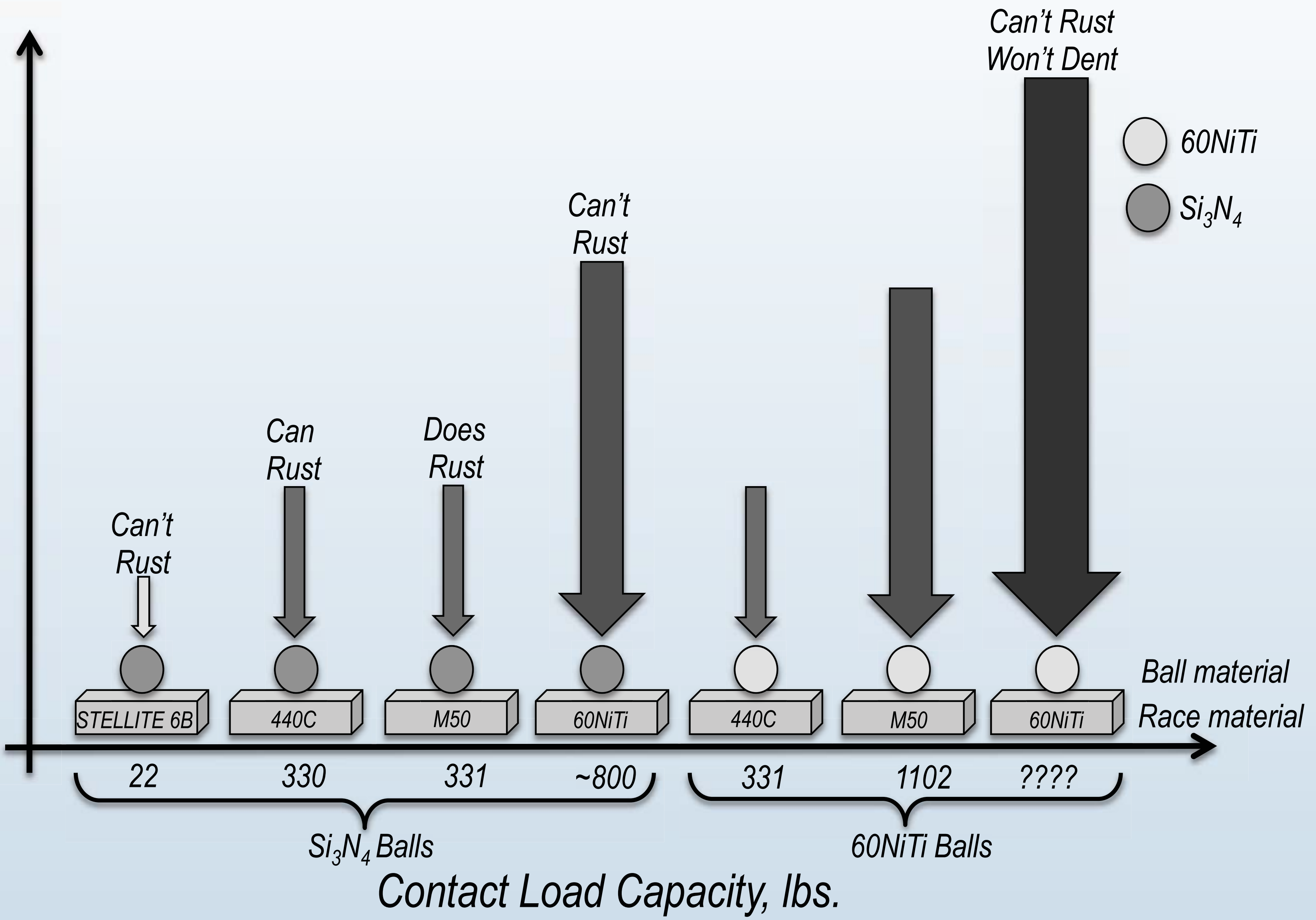
(12.7 mm diameter Si_3N_4 ball against 60NiTi plate)



Damage Threshold Load Capacity: Revised

(1/2" Diameter ball pressed into plate)

Indent test



Low modulus + high hardness +superelasticity = extreme load capacity

Rolling Contact Fatigue

(Updated test results: representative materials)

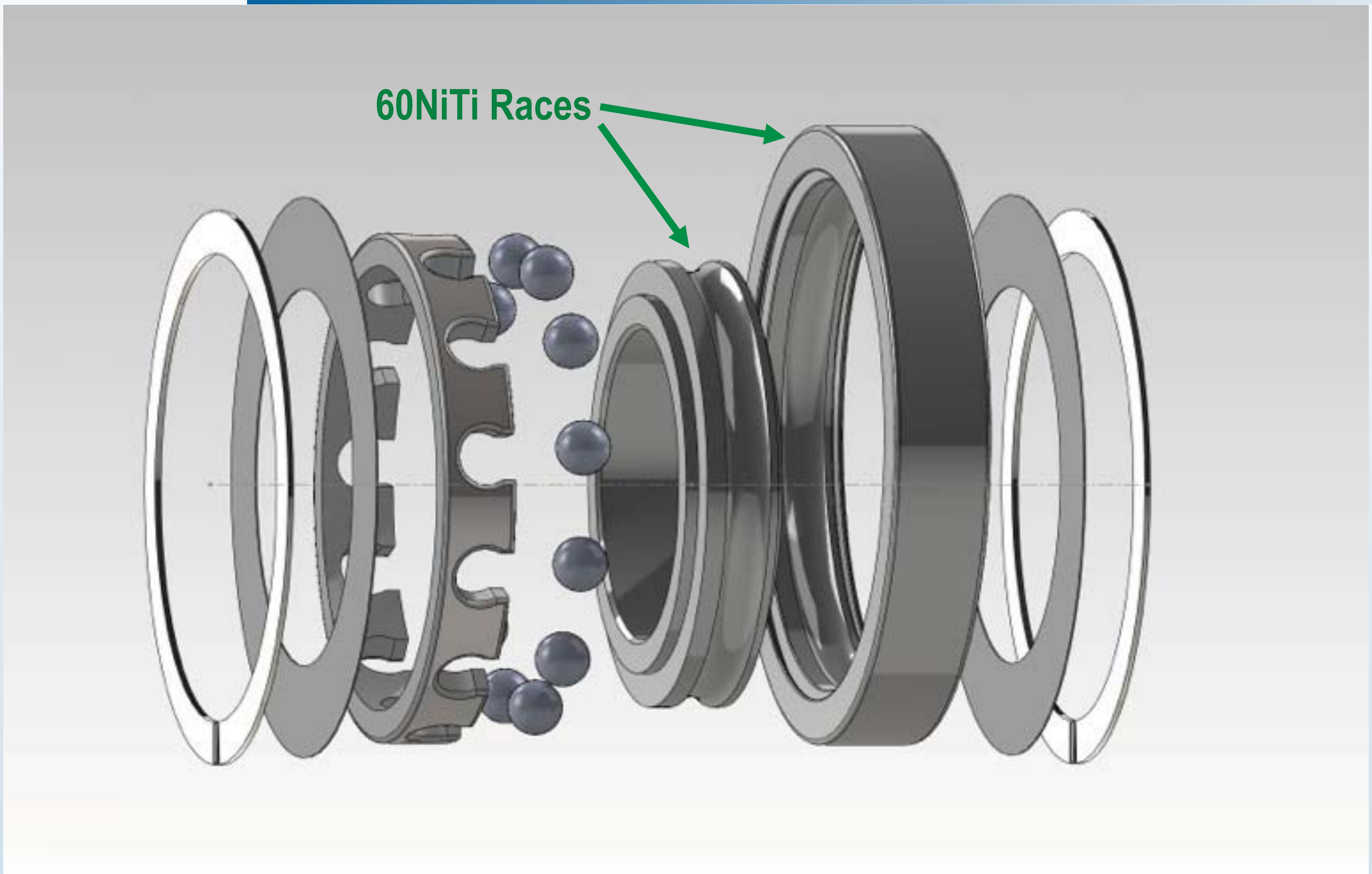
Table X-Three Ball-on-Rod Rolling Contact Fatigue Preliminary Results (test duration to first detected surface damage) {3600 rpm, steel balls, NiTi rods, oil drip lubrication}				
Rod Specimen	Peak Contact Stress (GPa)			
	1.7 GPa	2.5 GPa	3.3 GPa	4.1 GPa
PM-60NiTi (Baseline)	>800 hr	18-847 hr	<20 hr (tests ongoing)	<0.3 hr
PM-60NiTi (With inclusions)	131-800 hr	11-800 hr	0.2 to <236 hr	-------
60NiTi (Cast & hot-rolled)	13-800 hr	<5 hr	<5 hr	-------
59NiTi + X alloy (Cast)	>800 hr	>800 hr	0.1 to 970 hr	-------
59NiTi + X Alloy (Cast and extruded)	>800 hr	400 to 800+ hr	0.1 to <31 hr	--------

- Modern bearing steels yield long life to at least 3.5GPa.
- 60NiTi begins to exhibit permanent dents at stresses above ~4.0GPa.
- 60NiTi's life limiting fatigue stress is lower (~2) but is adequate for some applications. RCF results highly dependent upon material quality.

Status Report: 60NiTi Confirmed Attributes

- Data shows that 60NiTi is a good tribological material
- 60NiTi has excellent corrosion resistance.
- 60NiTi has good Rockwell C hardness.
- 60NiTi has good dimensional stability and polishes to a smooth surface finish.
- RCF data suggest good life if continuous stresses are modest (less than 300Ksi).
- Static load capacity enhanced by high hardness, low modulus and superelasticity.
- Ideal initial application would be chemically aggressive, exposed to shock loads but otherwise mechanically benign.

Expanded Drawing of DA Centrifuge Bearing



Bearing visualization aids design and manufacturing

Pathfinder Bearing Manufacturing

60NiTi Ingot Prototype

60NiTi Ingot Slice

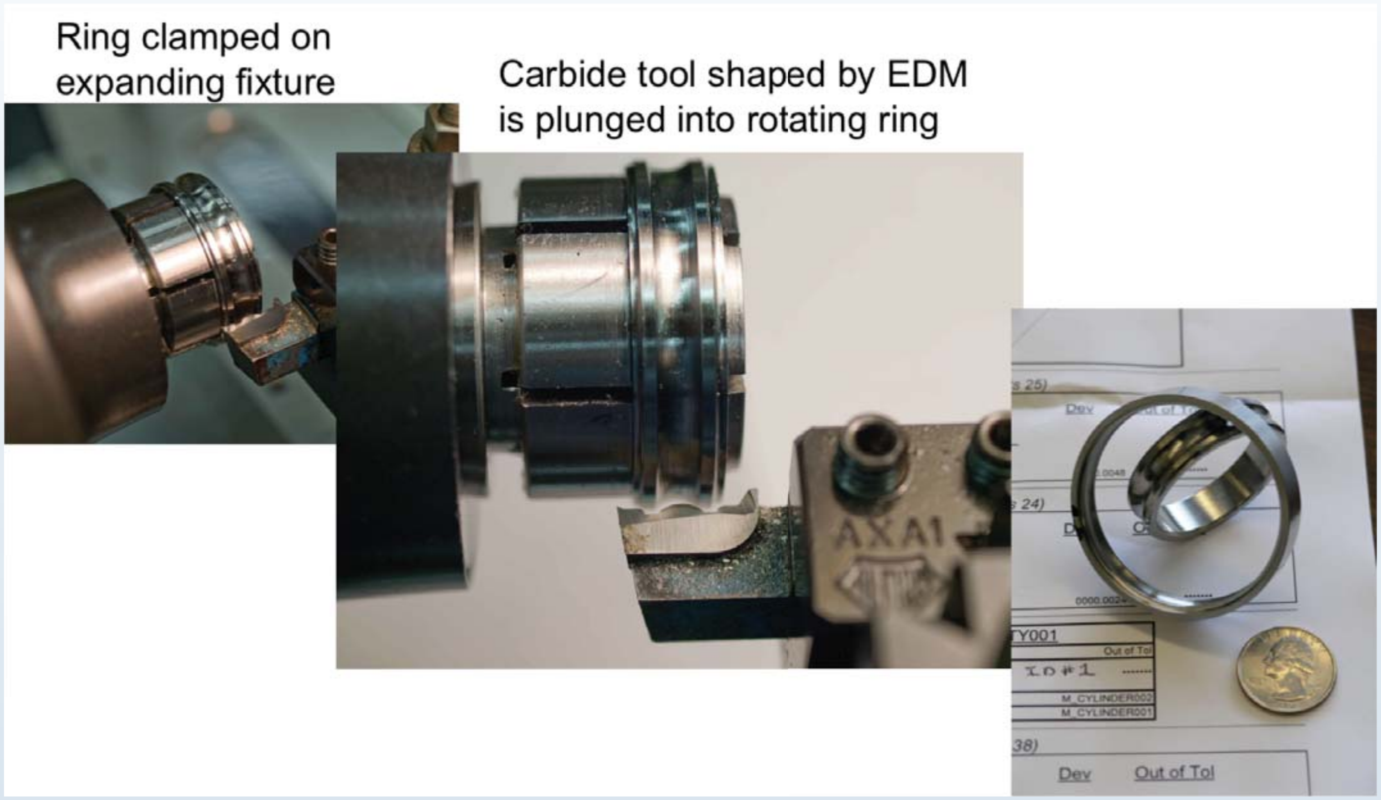
Wire Cut Blanks

QC Metallography

Microstructure and quality verified during manufacture.

Final steps include hardening (heat treat), finish grind and polish.

Pathfinder Bearing Manufacturing:
Race Turning Details



Turning tools, parameters and cutting fluid data shared with industry.

Pathfinder Bearing Manufacturing:
(Heat treatment development)

Unrestrained Races Distorted

Inconel race fixtures
(vented to allow quenching)

Process yields flat, round,
hardened races

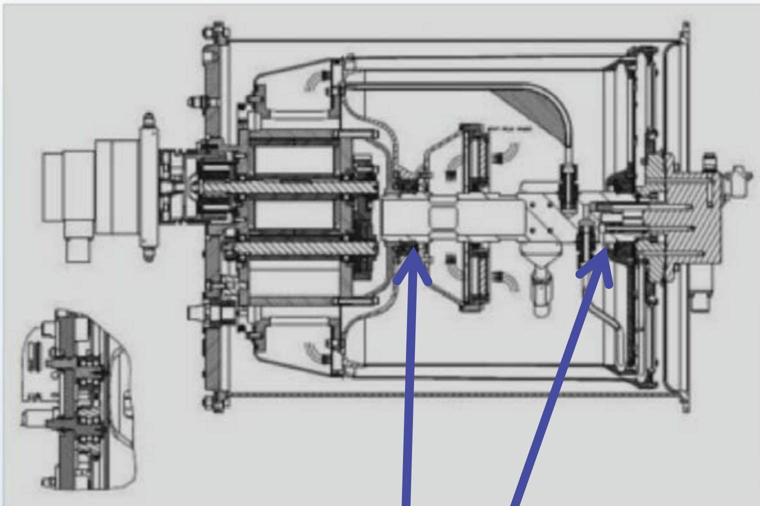
Final steps include finish grind, polish and assembly.

DA Bearing: 60NiTi-Hybrid (50mm)

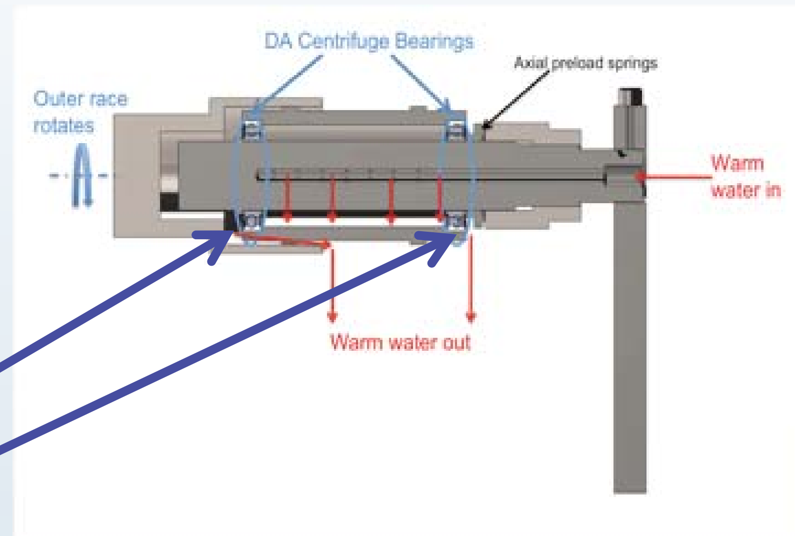
Ready for Testing

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..

Bearing Testing:
(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor

Short term (20 hour) tests run to prove operations.

Bearing Torque Results

Table XII-Test bearing spindle torque and power results for greased 60NiTi bearing pairs running in the presence of water at 25 and 65 C at beginning of test (BOT) and end of test (EOT)								
Load, N	25 C				65 C			
	Torque, N-m		Power, W		Torque, N-m		Power, W	
	BOT	EOT	BOT	EOT	BOT	EOT	BOT	EOT
89	0.37	0.57	7.7	11.9	0.37	0.88	7.7	18.4
178	0.57	0.53	11.9	11.1	0.90	0.99	18.9	20.7
267	0.57	0.57	11.9	11.9	0.99	0.99	20.7	20.7
356	0.61	0.65	12.8	13.6	0.99	0.98	20.7	20.5

- ***60NiTi bearings ran quietly and smoothly throughout the tests.***
- ***Baseline tool steel bearings began to run roughly and make noise after one-hour due to corrosion.***
- ***Corrosion resistant steels (like 440C) would be expected to survive such short duration tests in the presence of pure water without problems.***

DA Bearing: 60NiTi-Hybrid (50mm)

Post-Test Steel vs. 60NiTi-Hybrid

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

NiTi Bearing Take Away:

- 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.
- Employing low modulus, super-elastic, hard materials can lead to much more robust bearings and mechanical systems. Ideal for industrial, marine, spacecraft and aero bearings and components.
- 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.

ISS Tribology: Space Technology Pull

- Space imposes unique tribological challenges:
  - Vacuum, radiation and temperature extremes outside
  - Stringent safety and performance requirements inside
  - Loss of gravity enhanced effects (convective cooling, fluid drainage)
  - Novel machinery and systems (life support, exercise machines, etc.)
- ISS is the ultimate space development tool: (~3x of steel)
  - Deep support for developing advanced technologies
  - High stakes and payoffs
  - Cache of space is highly motivating
  - Ability to make and try (up-mass & down-mass)
  - ISS is viewed as “test lab located 250 miles away”
- Technologies developed for ISS provide terrestrial solutions:
  - Space mechanism “solutions” often find terrestrial applications (hybrid Si3N4 bearings, fluorocarbon oils, NiTi bearings)
  - Closed loop water and air purification systems (valves, pumps, bearings)
  - Expect the unexpected.

Thank You!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