Space Tribology: An Introduction

TAMU Lecture

Dr. Christopher DellaCorte

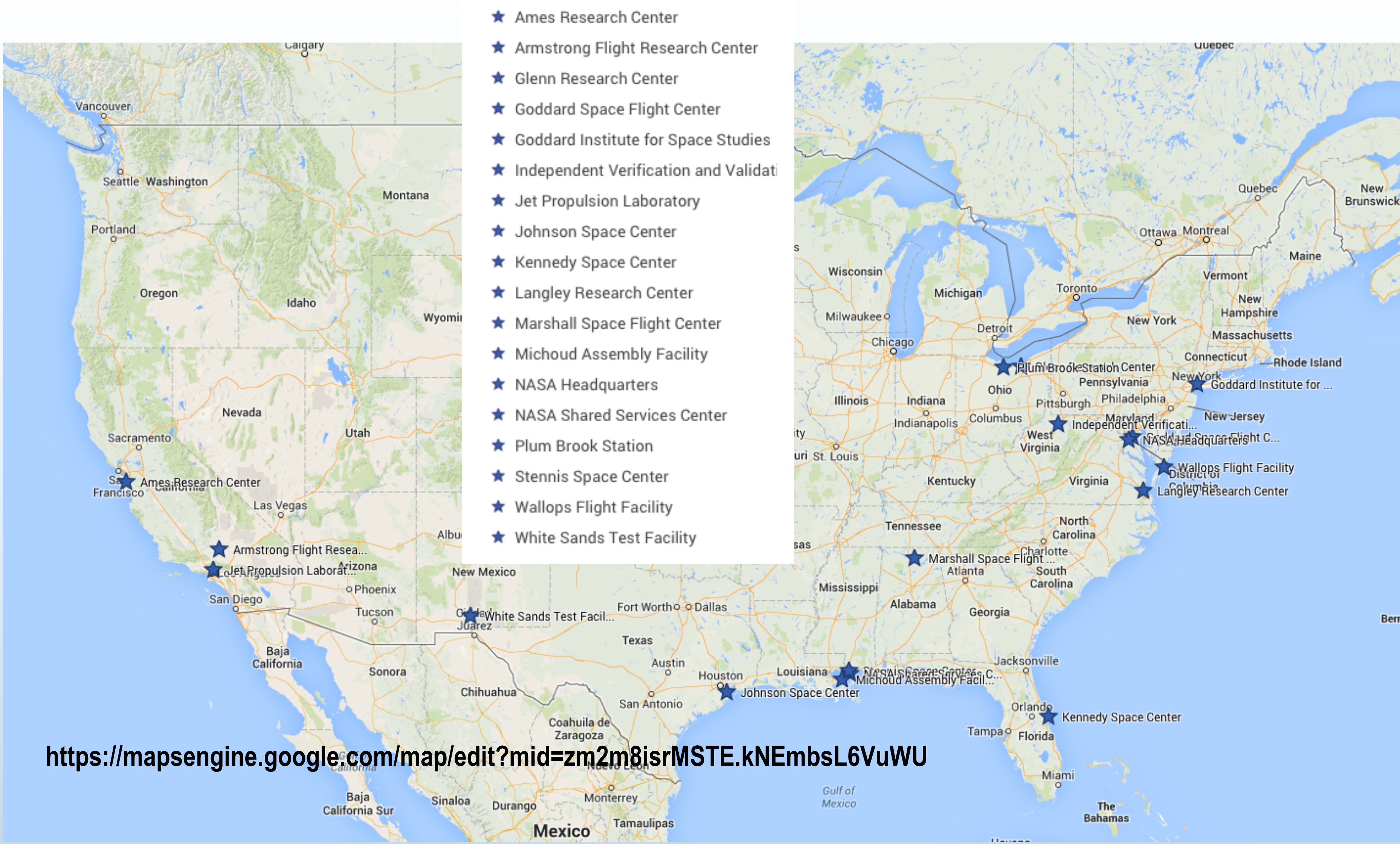
Senior Technologist, Tribology

NASA

Cleveland, Ohio

<u>TAMU Introduction to Tribology Class</u>
Virtual Lecture
April 8th , 2021

NASA: Not just "Houston" and "Kennedy"



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Tribology: Not Just about “Friction”

- Tribology
  - <u>Root</u>: From the Greek “tribos” which means to “rub”.
  - <u>Suffix</u>: “ology” the study of. Tribology is the ”study of rubbing?”
  - <u>Colloquial</u>: The study of friction, wear and lubrication.
  - <u>General Scope</u>: Bearings, gears, lubricants, friction and wear.

Space Environment: Not just one "place"

- Space environment varies:
  - <u>Iconic Space Environment</u>: hard space vacuum, atomic oxygen and UV radiation exposure, -100 to +100º C temperature swings.
  - <u>Inside a spacecraft</u>: Could be vacuum or pressurized with a gas (air, argon, etc.) held at ~20-50º C
  - <u>General</u>: Zero-g thwarts normal fluid flows (convection, drainage, etc.),

Space Tribology: A bit of “Everything”

- Examples:
  - <u>Dry Film Lubricants (DFL)</u>: PTFE, graphite, MoS_2, silver, lead, gold.
  - <u>Grease</u>: Vacuum stable, flow when cold, don’t outgas. Used for bearings, gears and latches.
  - <u>Mechanisms</u>: flexure springs (movement w/o tribology, bearings, bushings, gears, hinges, seals, etc.),

Tribology: Friction, and Wear

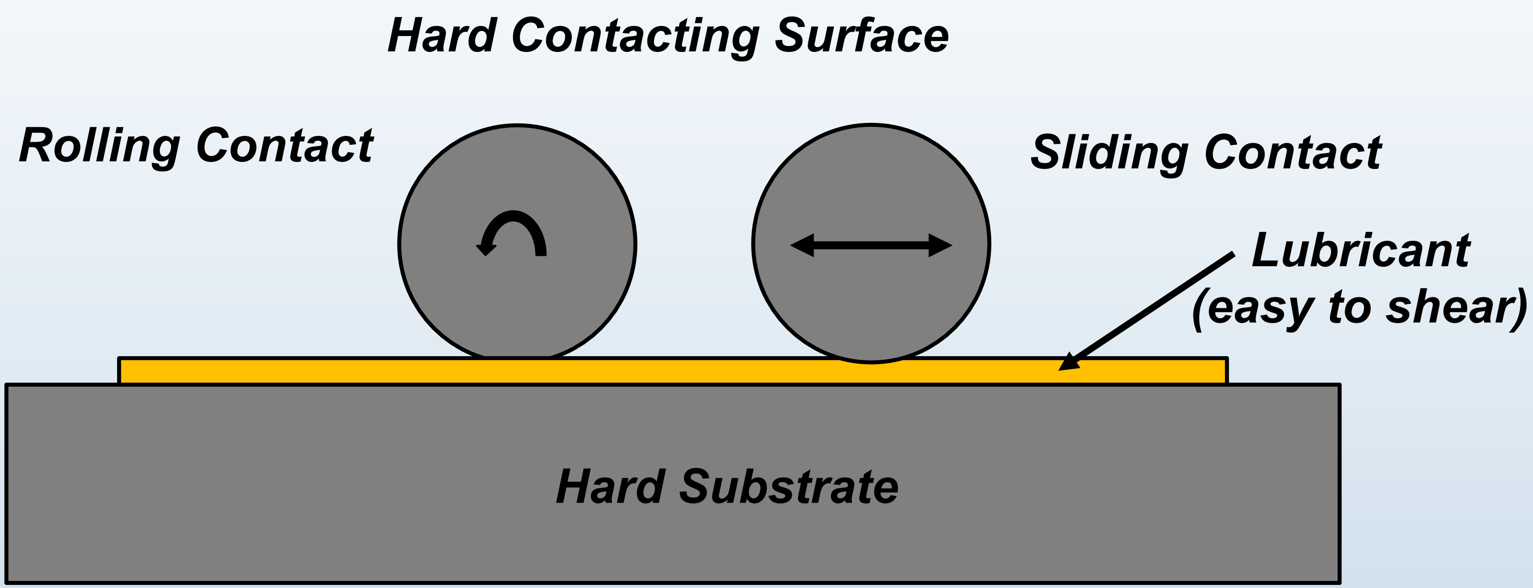
- **Basic underlying principles:**
  - **Two surfaces in relative motion contact.**
  - **Surface asperity tips touch each other**
    - **Friction forces are proportional to aperity material properties (hardness, strength).**
    - **Wear occurs when asperity tips break.**
  - **Even rolling creates asperity tip contact and sliding at the micro-scale.**
    - ***There is no such thing as "perfect rolling contact"***

Tribology: Lubrication

- Basic underlying principles:
  - Friction reduction is achieved by reducing the local material strength at the contact interface.
  - Friction reduction is enhanced by minimizing the number of asperities that touch (limiting contact area).
  - Effective lubrication occurs when something soft (lubricant) is placed in between two hard contacting surfaces that are in motion.

Tribology: Lubrication-schematic

- Effective lubrication occurs when something soft (lubricant) is placed in between two hard contacting surfaces that are in motion.



Note: Lubricant could be oil, grease, solid lube, soft oxide layer, etc.

Lube Selection: Depends on application

- <u>Solid Lubes</u>:
  - +: Stay put, work cold and hot,
  - - : limited life, cannot replenish.
- <u>Oil</u>:
  - +: long life, good heat transfer,
  - - : wicks and pumps needed for zero-gravity.
  - - : Many oils become too thick or even freeze at space temperatures.
  - - : Many oils evaporate in the space vacuum.

Lube Selection: continued

- <u>Process fluids:</u> (e.g., lube with pumped product)
  - + : no contamination issues.
  - - : needs sealed systems, process fluids are often poor lubricants (water, ammonia, CO_2).
- <u>Grease:</u>
  - Is the most common space lubricant.
  - Combines best attributes of other lubes
  - Lasts a long time, stays put, “tailorable” for specific attributes.

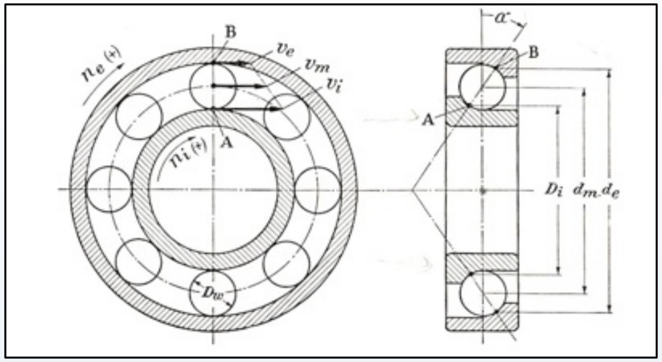
ISS: Self-Contained City

ISS: Every kind of tribology “Everything”

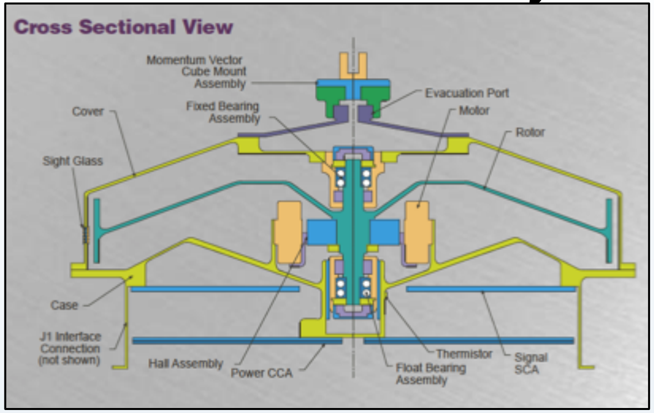
- Examples:
  - Bearings: Ball bearings, roller bearings, sliding bearings.
  - Gears: intermittent use, continuous duty, wet lubed, dry lubed, cold and hot.
  - Mechanisms: pumps, hatches, fans, exercise equipment, spacesuit joints, solar array drives, slip-rings, control moment gyros, momentum wheels, robotic arms, etc.

The things that need to be lubricated:

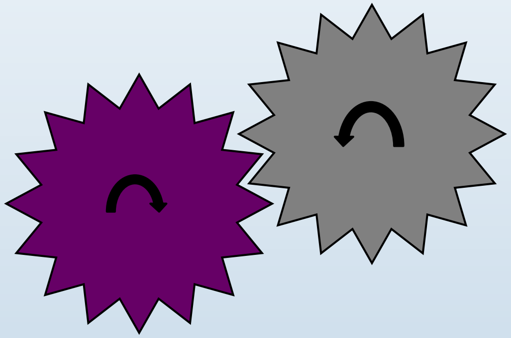
Bearings of all types



Reaction Wheels and Gyros



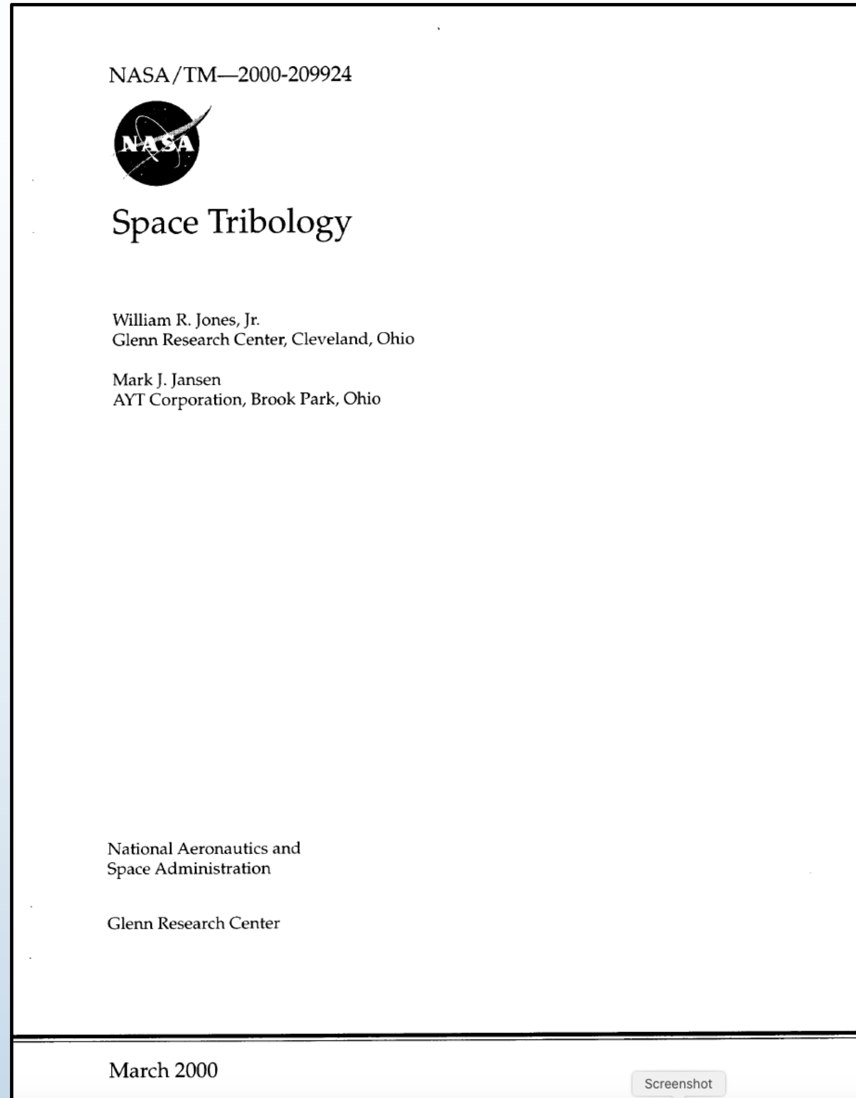
Gears: for power transmission and actuation



Blowers and pumps

Space Tribology: Key References

- **<u>Excellent Space Tribology Information Sources</u>:**
  - W.R. Jones, et. al: “Space Tribology,” NASA TM-2000-209924.
  - E.W. Roberts: “Space Tribology: Its Role in Spacecraft Mechanisms,” J. Phys. D: Appl. Phys. 45 (2012)503001.
  - https://en.wikipedia.org/wiki/Space_tribology



NASA/TM—2000-209924

Space Tribology

William R. Jones, Jr.
Glenn Research Center, Cleveland, Ohio

Mark J. Jansen
AYT Corporation, Brook Park, Ohio

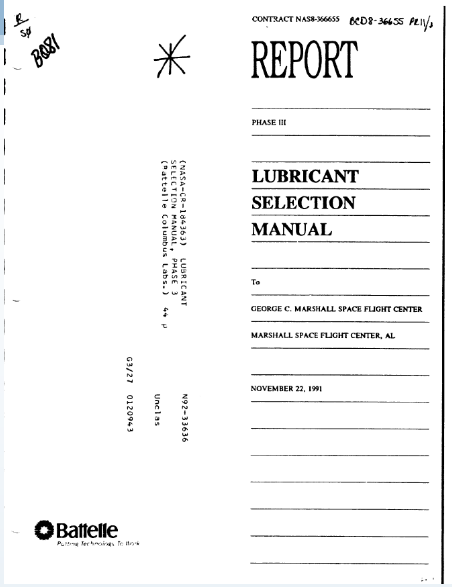
National Aeronautics and
Space Administration

Glenn Research Center

March 2000

Space Tribology: 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



Space Tribology: Generalizations

- Lubrication in space is a challenge
  - Exterior locations: Extensive use of vacuum compatible grease, solid film lubricants, radiation shielding.
  - Spacecraft interiors: Grease, PTFE based solid lubricants, fire/toxicity/odor concerns.
  - Everywhere: Wear debris minimization and control, maintenance-free are key drivers. Active thermal control/cooling is norm.

Lean on heritage, verify and have a back-up

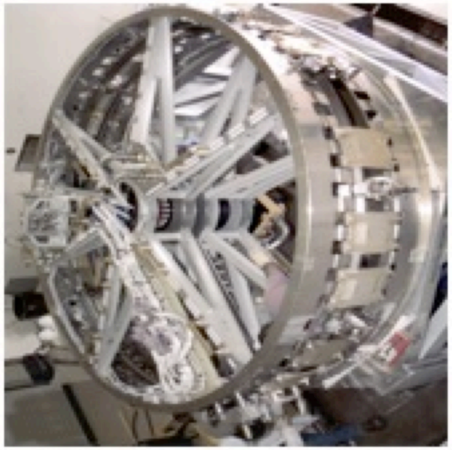
- Space tribology design rationale
  - <u>Heritage</u>: Rely upon proven experience, use what ever solution/lubricant has worked in space in the past.
  - <u>Testing</u>: Conduct extensive ground tests of new technology before flight.
  - <u>Redundancy</u>: Design back-up systems to achieve mission success even if the mechanism wears out or fails.

Space Tribology: 3 Teaching Examples

- Every problem is different:
  - Failure Analyses: Something breaks, we must understand why before a solution can be developed.
  - New approaches: testing must be done to guide new designs before making major investments in space hardware.
  - In-Space research: R&D is sometimes done during space missions to expand capabilities.

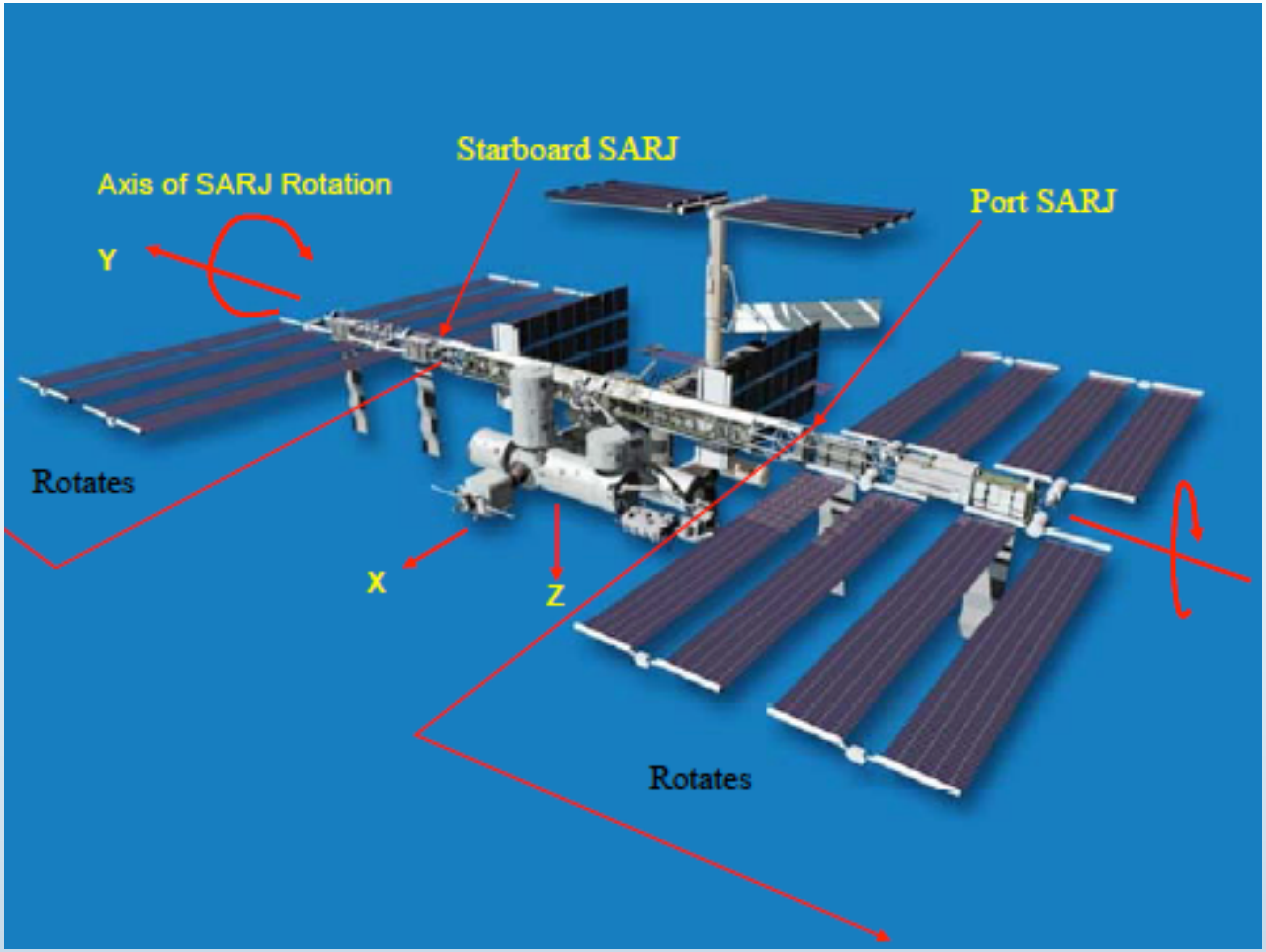
#1-Failure Analysis: What went wrong?

- SARJ Bearing Failure:
  - Solar Alpha Rotary Joint (SARJ)
  - Solar panel wing bearing.
  - Continuous slow rotation
  - Turns one rev every 90 minutes
  - Vital to ISS operation. Failure not an option.



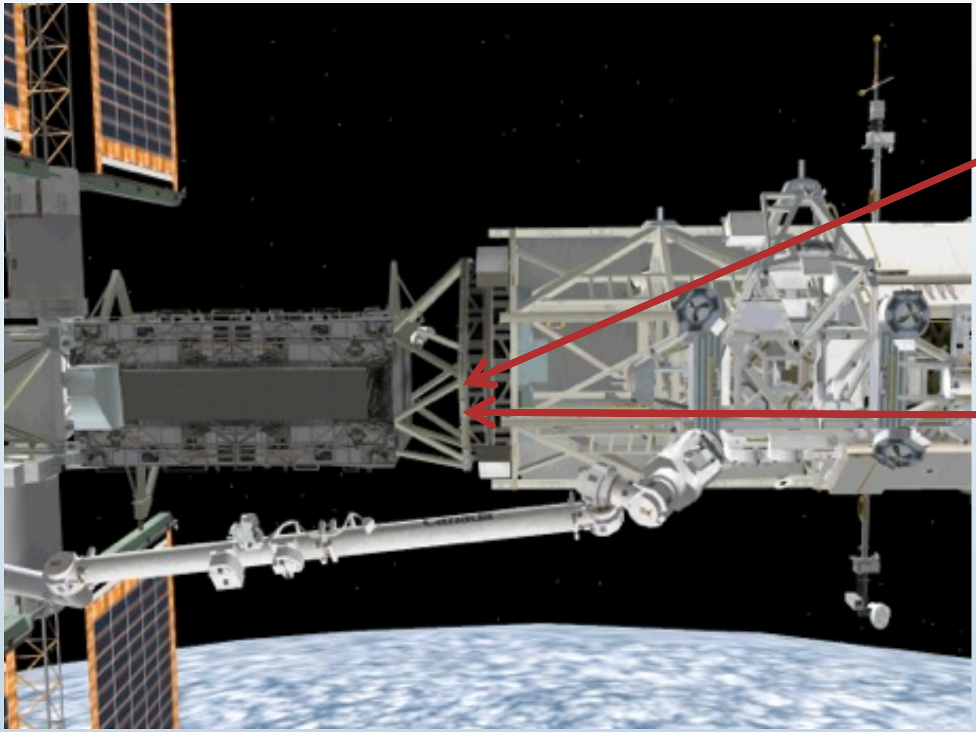
ISS: Solar Alpha Rotary Joint (SARJ)

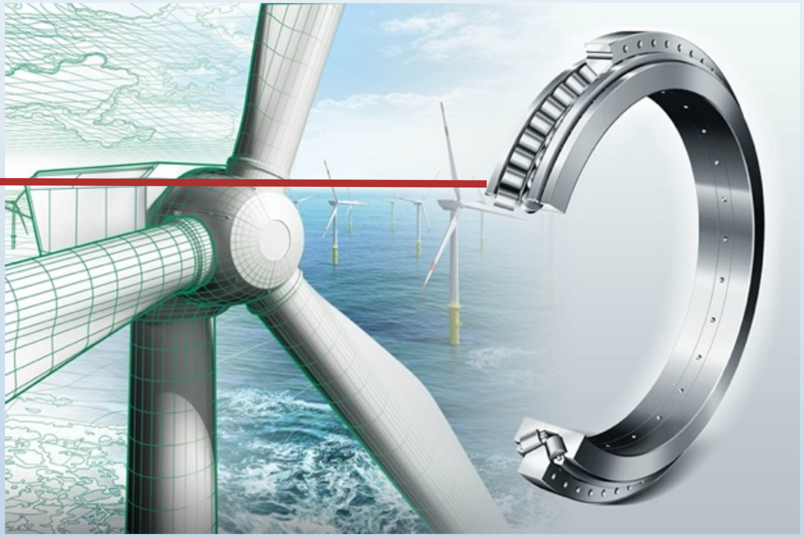
- Big bearing allows solar panels to follow sun.



SARJ Bearing: Like Wind Turbine Bearing

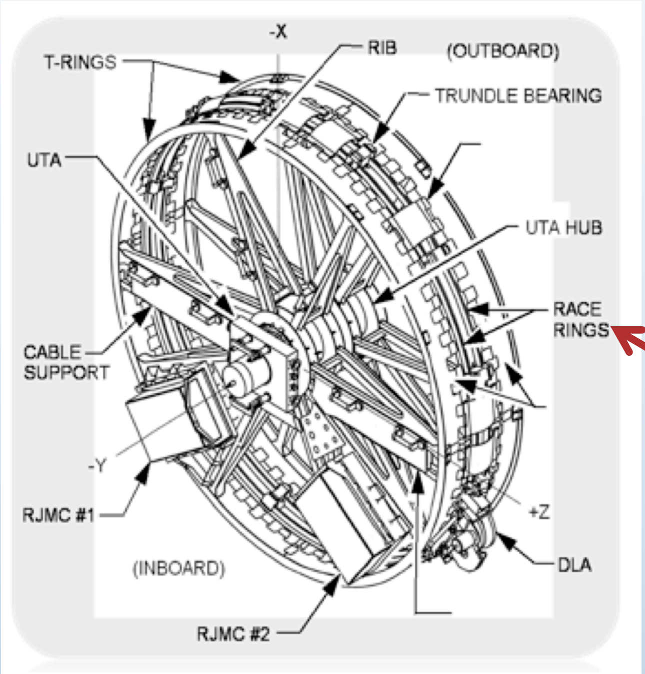
- 3-meter diameter bearing
- Turns slowly and must be smooth
- Similar scale to large wind turbine bearings

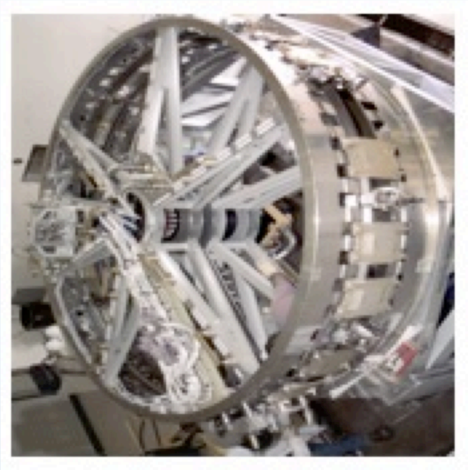


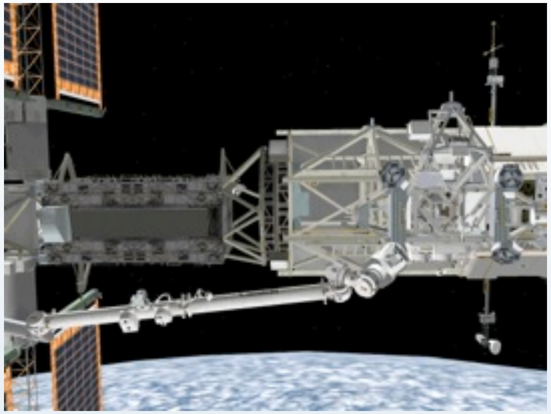


SARJ Hardware

- SARJs:
  - Design complex.
  - Can be replaced or repaired in space



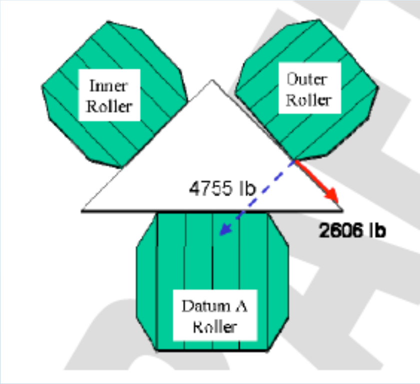




Bearing made for long-life, but designed to allow replacement by astronauts (never proven before).

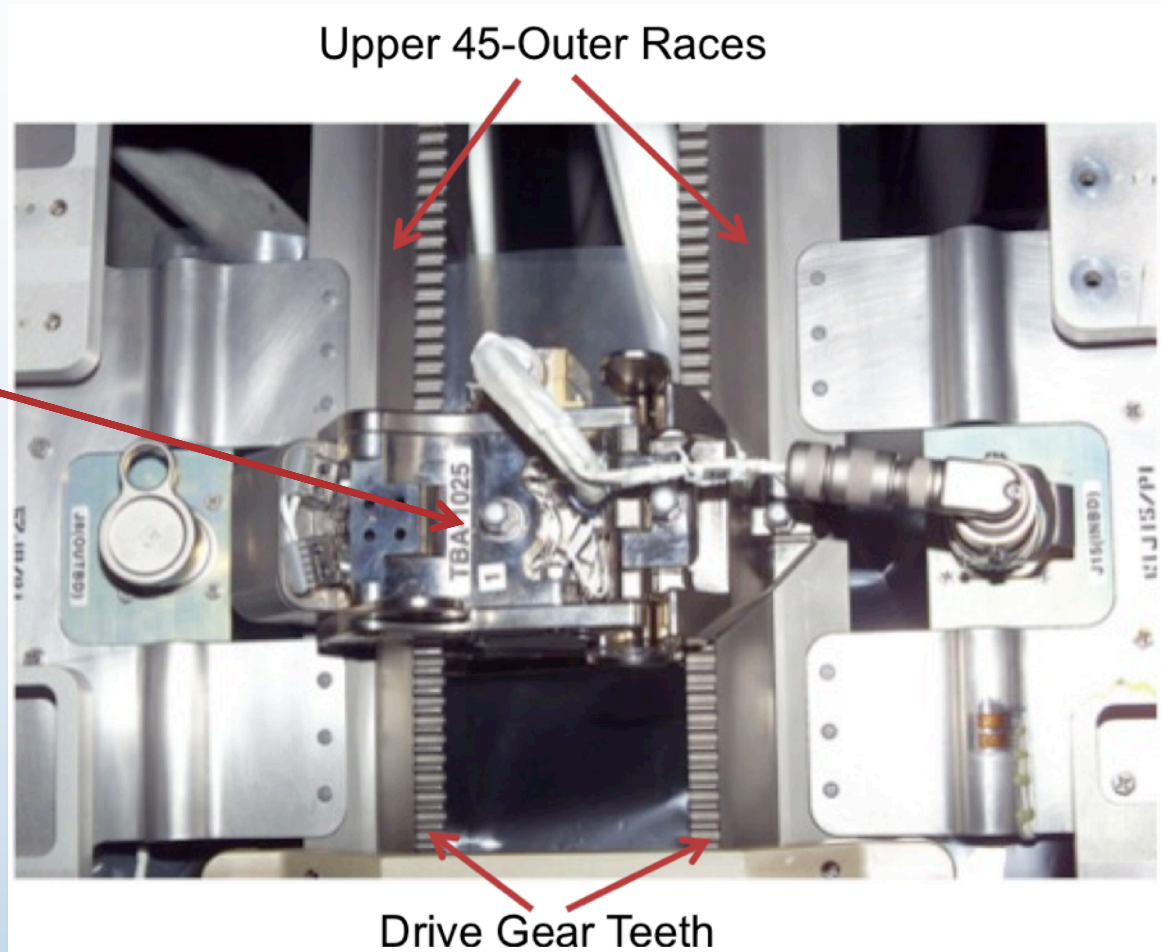
SARJ Bearing (Close up view)

- Bearing race rings are triangle cross-section (shape).
- Races turn inside three gold plated (solid lube) rollers.
- Each roller contains small ball bearings with PFPE based grease.



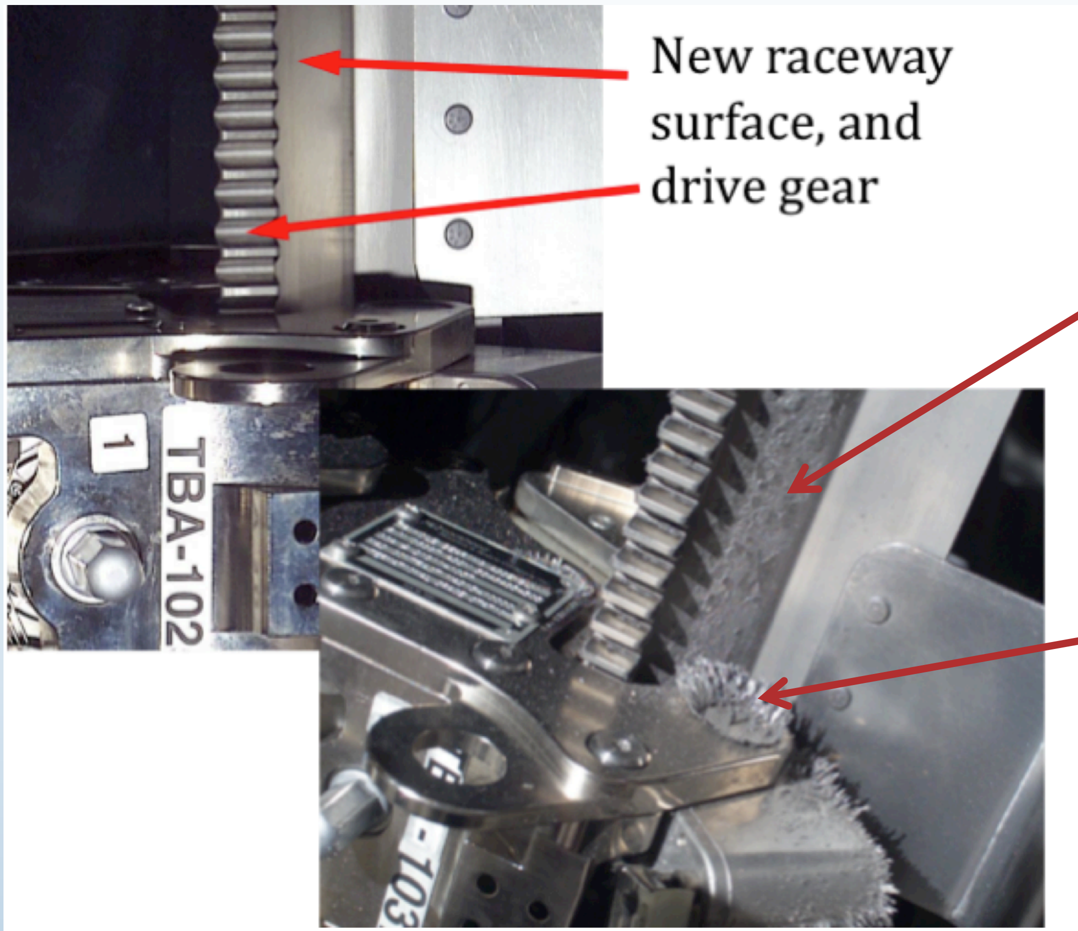
SARJ: When new on ISS

- Race surfaces are smooth and clean.
- Rollers (hidden under trundle) allow races to turn easily.



SARJ: Bearing stopped turning?

- **Astronaut Extra Vehicular Activity (EVA-spacewalk)**
  - **Race was not smooth and clean any longer.**
  - **Wear debris was everywhere…samples collected.**

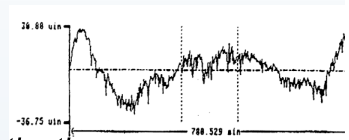


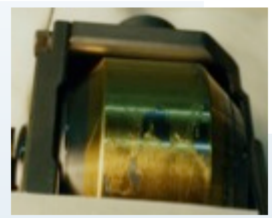
Investigation: “how did it break?”

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.

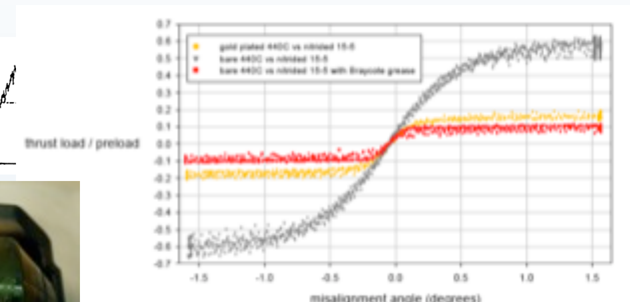
Problem

Investigation



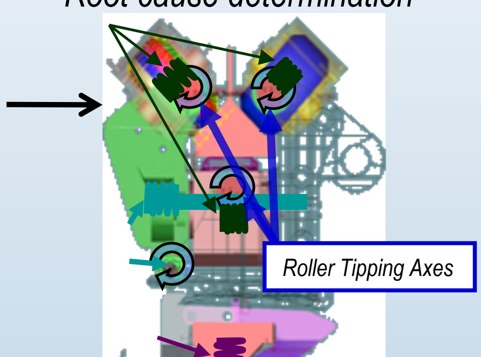


Design analyses and records search



Tribology test data and expertise

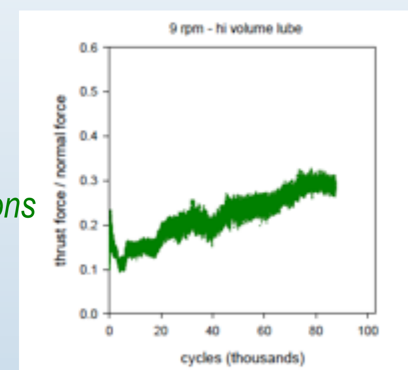
Root cause determination



Understanding

T. Krantz and C. DellaCorte (RXN)

Recovery-Operations



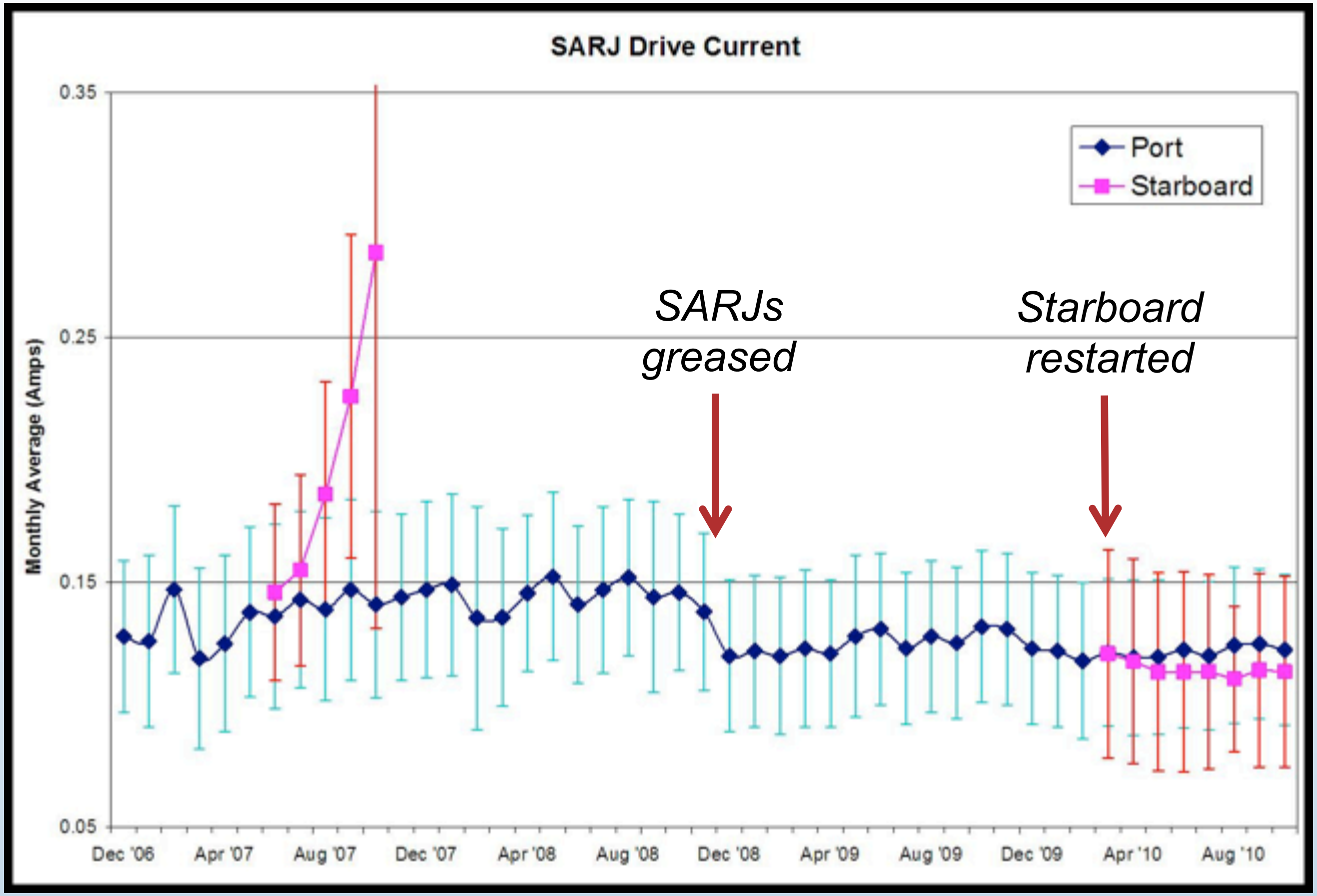
Lube life testing: ongoing

Repair: “How can we fix the SARJ?”

- Ground tests <u>and</u> analyses showed that grease reduces friction and is needed.
  - STS-126 trained for SARJ repair and recovery.

Grease: "It worked and just keeps going!"

- Grease lubrication added November 2008.
- NASA watches SARJ friction every minute, 24/7.
- Over ten years later the SARJ bearings are ok.



Lessons Learned:

- All bearings need lubrication.
- Grease is good.
- Gov't Report: NASA TP-2011-217116

NASA/TP—2011-217116

ISS Solar Array Alpha Rotary Joint (SARJ) Bearing Failure and Recovery: Technical and Project Management Lessons Learned

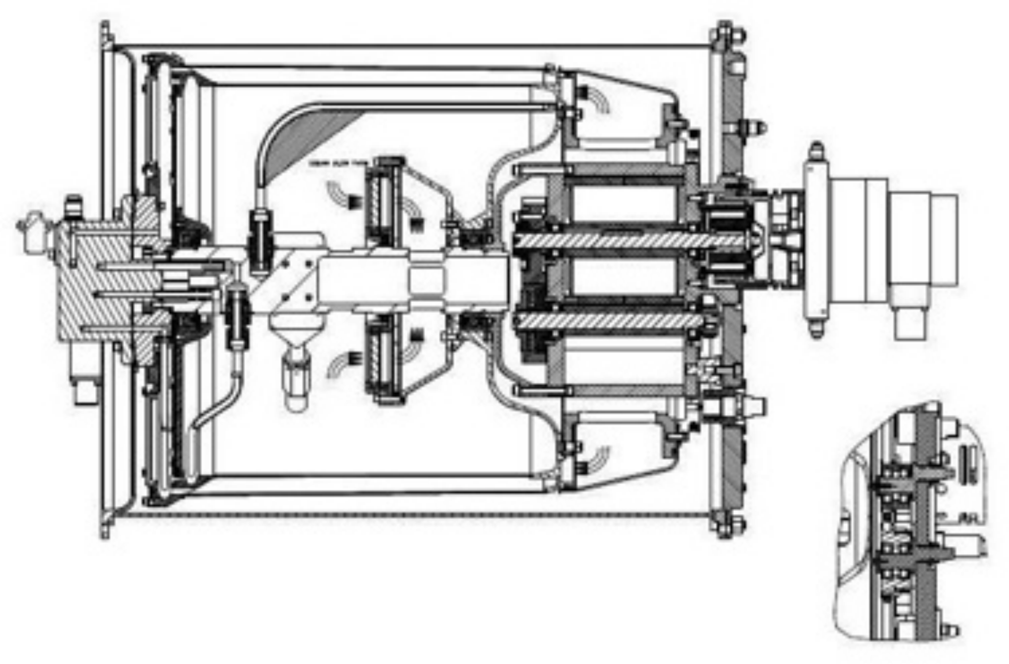
Christopher DellaCorte and Timothy L. Krantz
Glenn Research Center, Cleveland, Ohio

Michael J. Dube
Goddard Space Flight Center, Greenbelt, Maryland

August 2011

https://ntrs.nasa.gov/search.jsp?R=20110015384

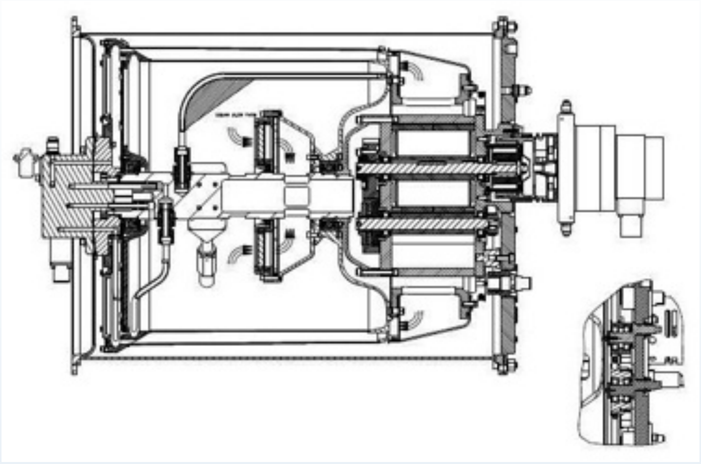
#2-New Approaches: NiTi ball bearings



- ECLSS Distillation Assembly: Purifies dirty water
  - Liquids (urine, sweat, spit, etc.) are collected.
  - Mixed with acids to kill bacteria.
  - Sent through a rotating (bearings) distiller (warm) process.

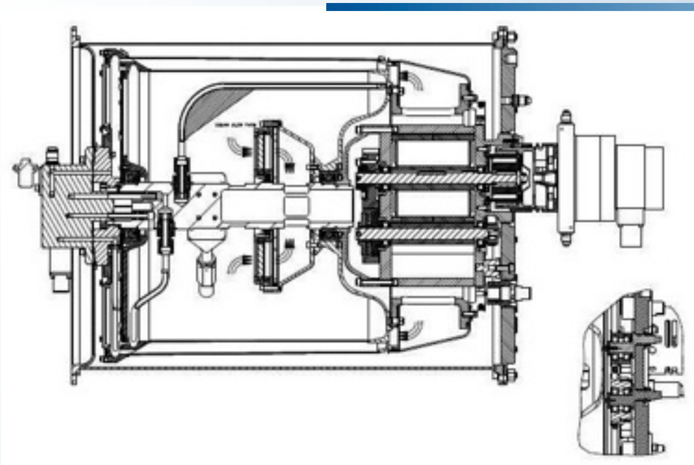
ISS: Water Recycling

"Toilet" → *"Distillation Assembly"* → *"Refreshing!"*



- <u>**ECLSS Distillation Assembly**</u>**:**
  - **Rotating drum is heated to boil dirty acid water and create steam.**
  - **Steam is cooled, condensed and filtered to produce clean water.**
  - **Inside ISS, warm, wet, corrosive environment.**

Water Recycler: Needs new bearings



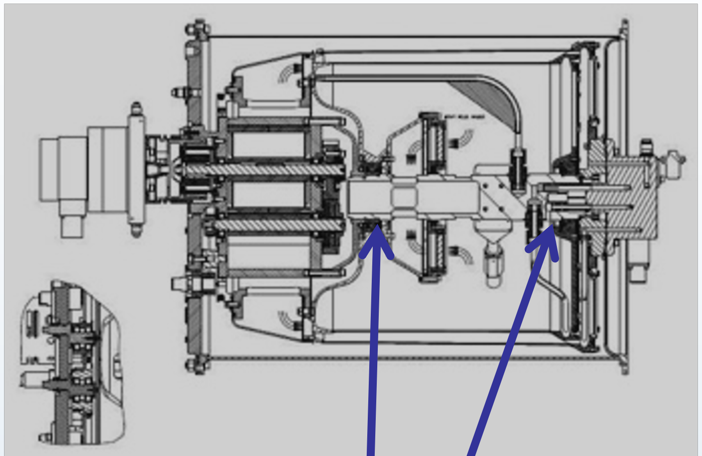
Steel Bearing (rust)

NiTi Bearing (rust-proof)

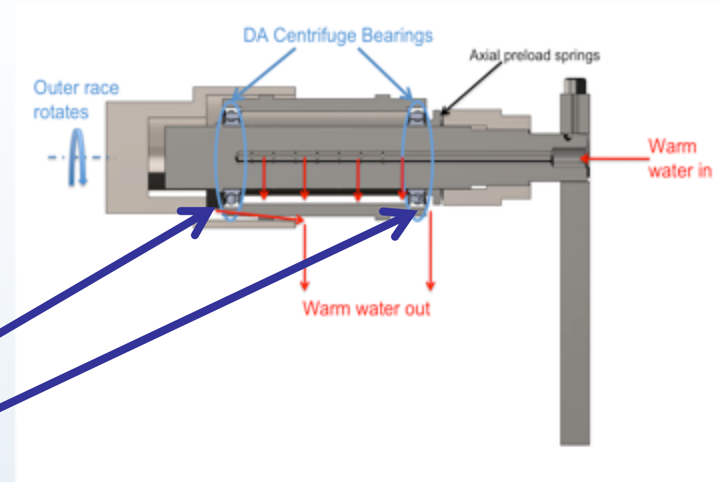
- <u>ECLSS Distillation Assembly</u>: Bearing problems
  - Original steel bearings rusted and failed.
  - Cobalt alloy bearings were too soft and failed
  - NASA invented new NiTi alloy that is hard and does not rust but needs lubrication.
  - Selected a water resistant Li-base grease with synthetic PAO oil and non-toxic additives.

Bearing Testing: NASA lab
(Warm, wet, slow conditions)

DA Cross Section



DA Urine Processor Simulator

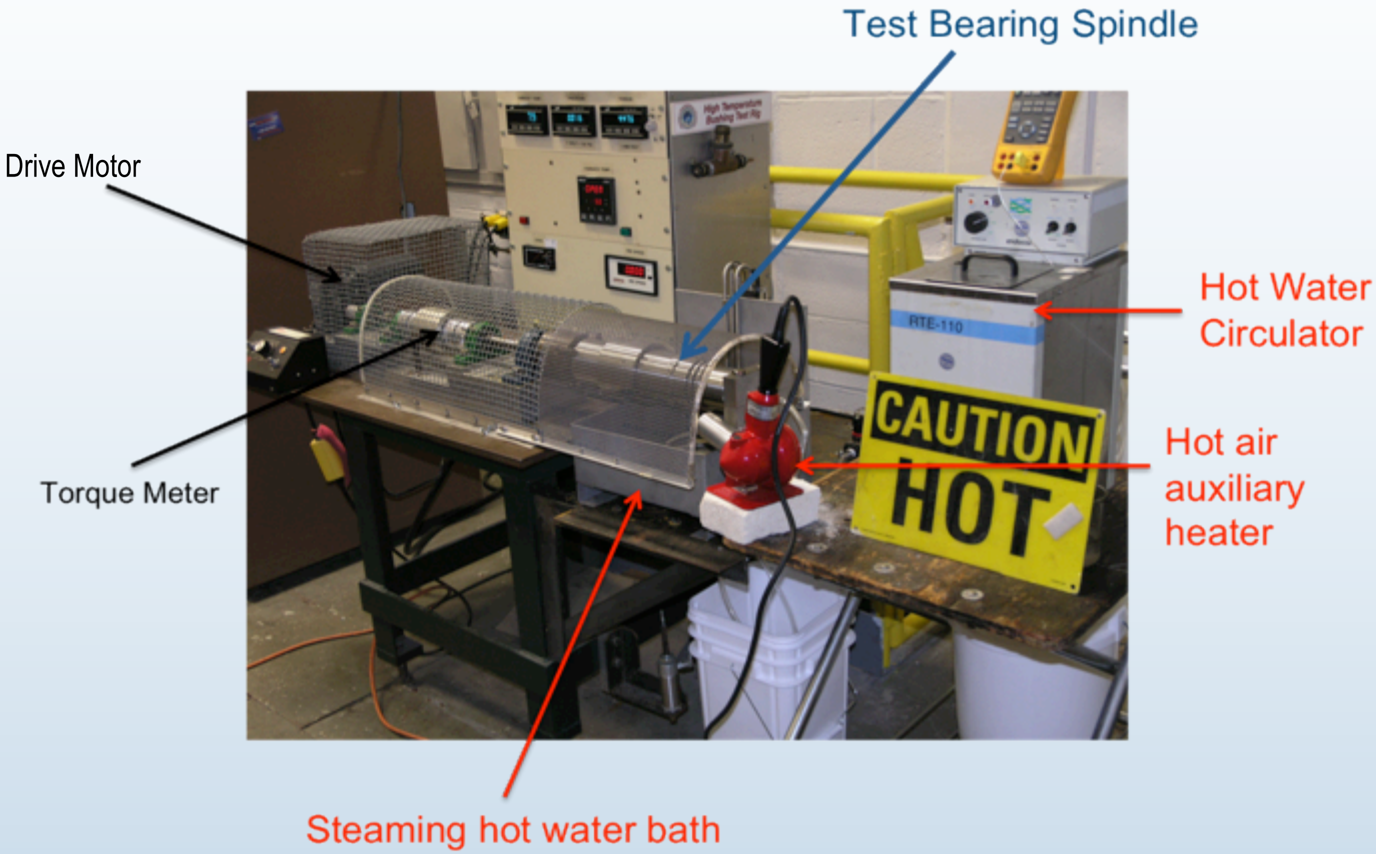


DA Centrifuge Bearing Test Rig
Spindle Components

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

Bearing Testing: Grease works again!
(Warm, wet, slow conditions)

Lab Configuration of DA Urine Processor



Long tests (10 000 hours) prove that greased NiTi bearings work well.

Lessons Learned:

- **Bearing material selection is critical.**
- **All bearings need lubrication.**
- **Grease is good but could be better (waterproof and acidproof).**
- **Gov't Report: NASA TM-2012-216015**

NASA/TM—2012-216015

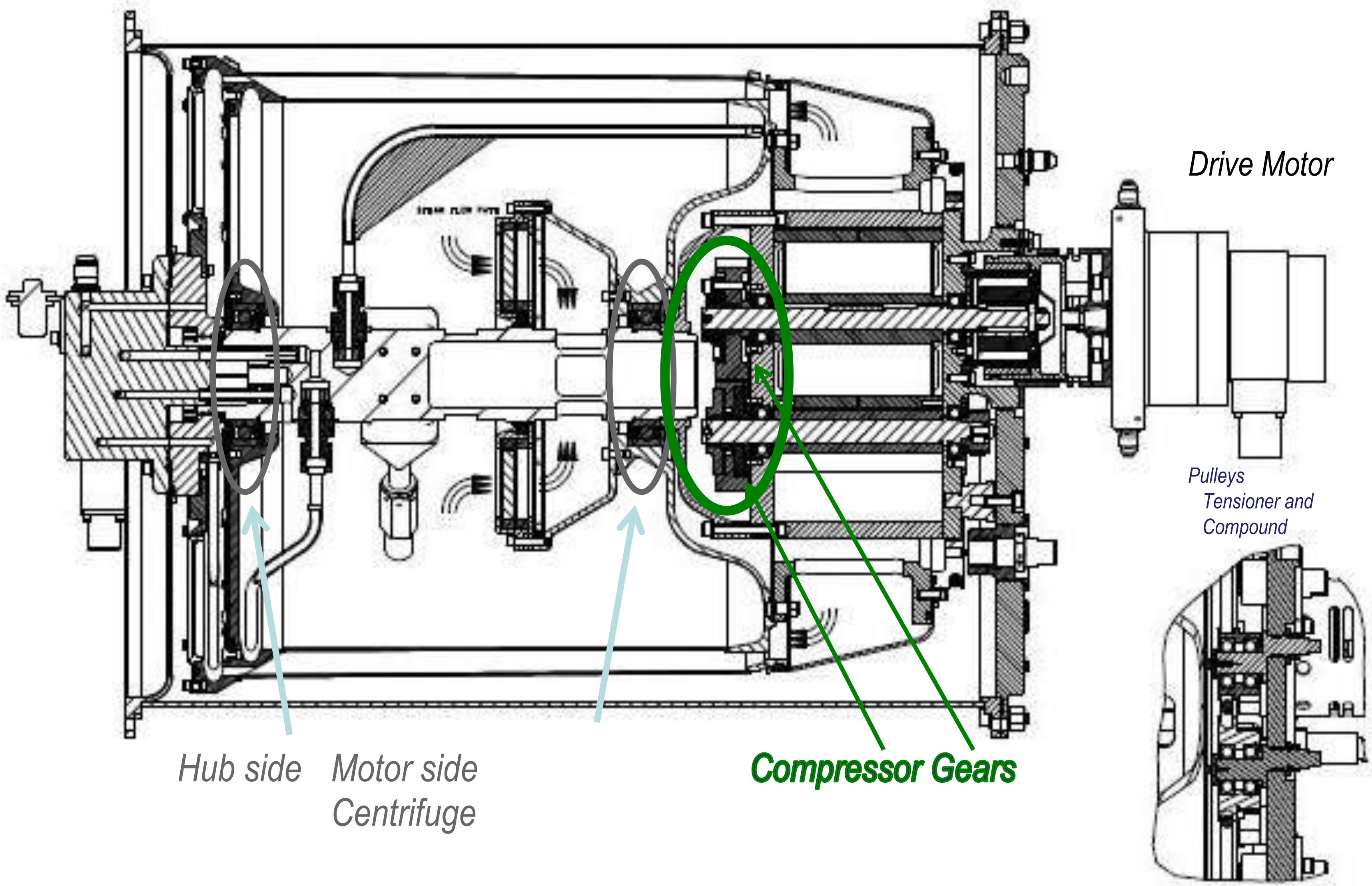
Design and Manufacturing Considerations for Shockproof and Corrosion-Immune Superelastic Nickel-Titanium Bearings for a Space Station Application

Christopher DellaCorte and Walter A. Wozniak
Glenn Research Center, Cleveland, Ohio

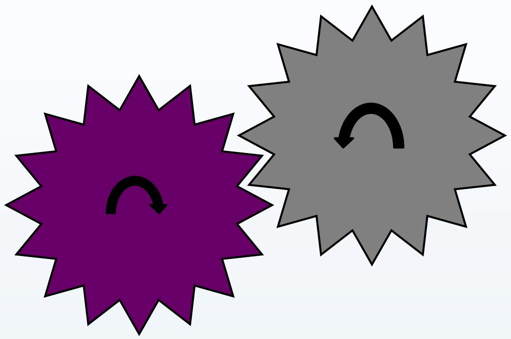
May 2012

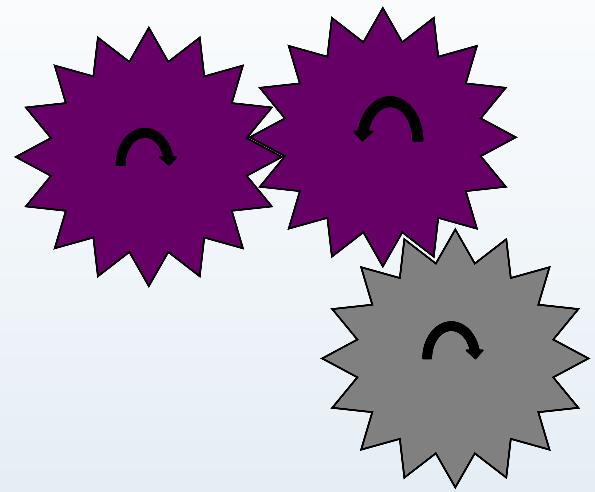
https://ntrs.nasa.gov/search.jsp?R=20130001675

New Approaches: 60NiTi gears



New Approaches: Seeking better gears





Environment: Warm, wet steam, light load, high speed

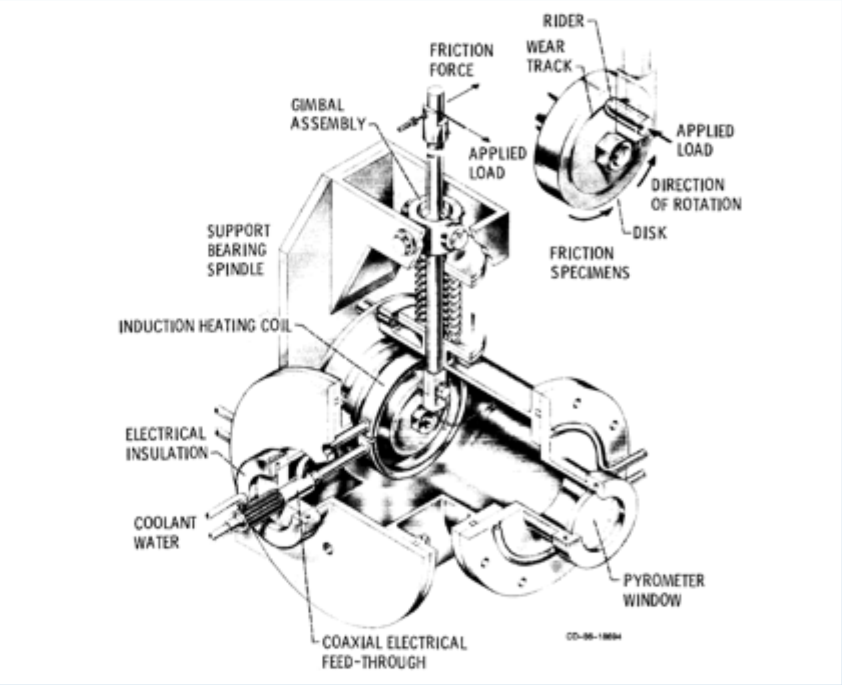
Problem: Polymer gear wear and dimensional instability.

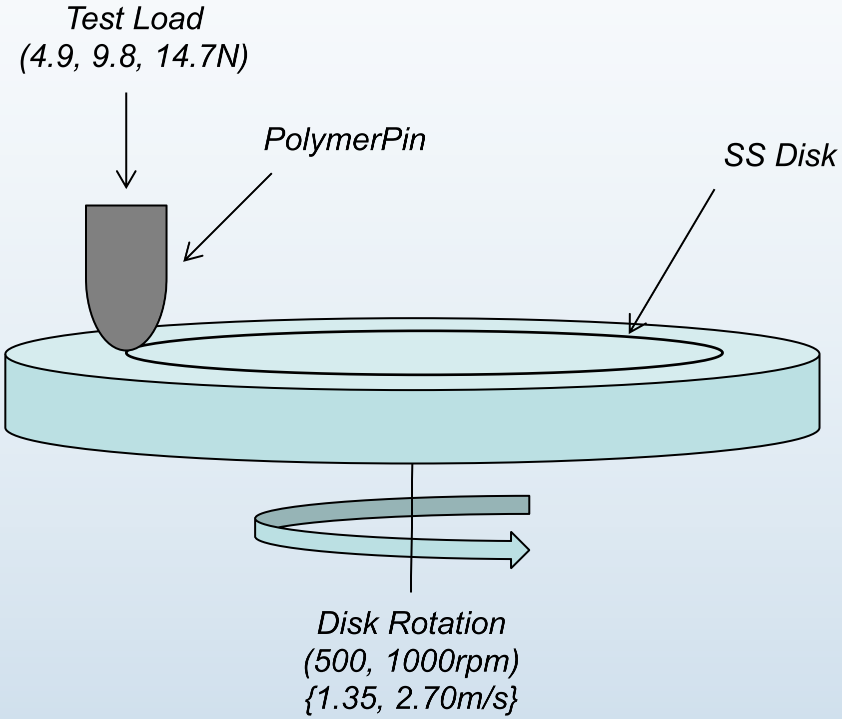
Candidate Solution: 60NiTi gears with solid lube coating and additional transfer lube if needed.

Problem: No solid lube-60NiTi data available to guide design.

DA GEARS:Tribology Simulation

•Pin-on-disk sliding test designed to mimic gear tooth-tooth contact.
•Load and speed chosen to bracket gear application.
•Survey-type experiments done over range of load-speed combinations to find pair that produces wear surfaces that match worn Polymer/SS gear surfaces.*
•Data output: friction coefficient, pin wear factor {wear vol./(load x distance)}



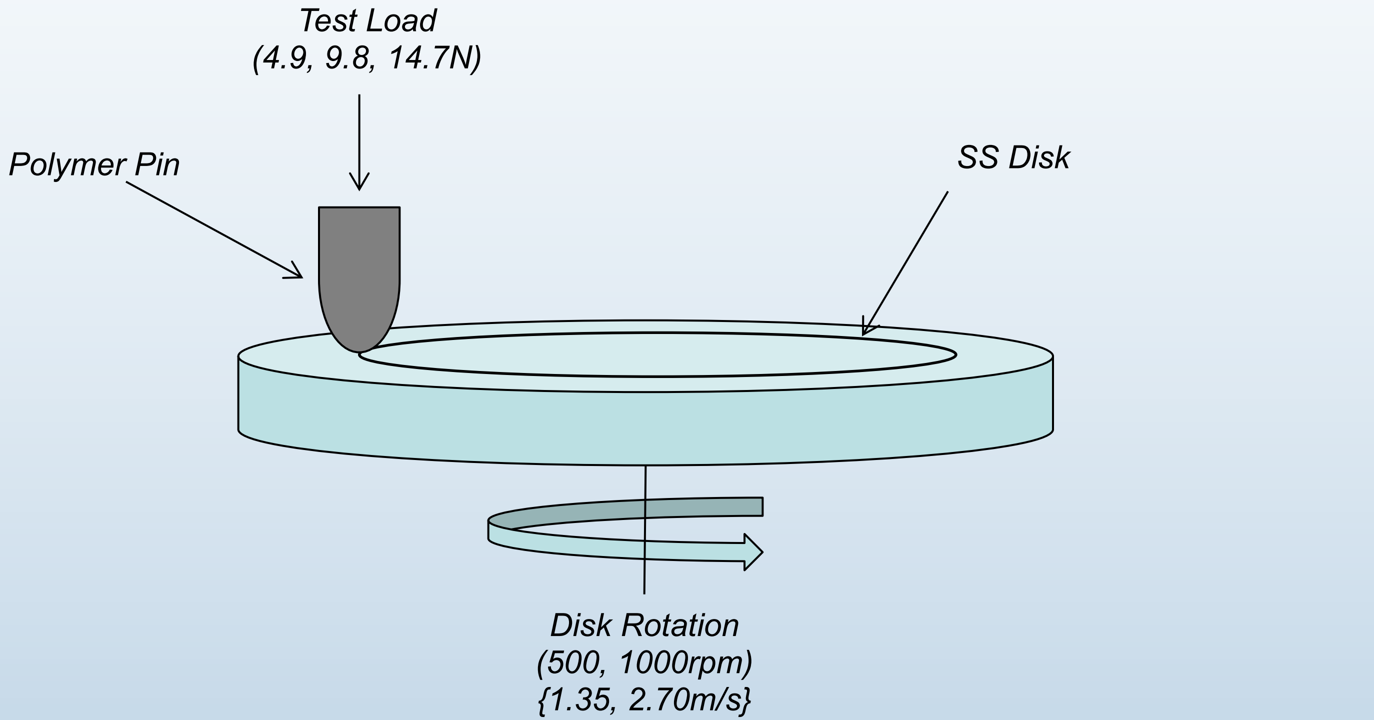


**Selected sliding conditions: 4.9N load, 2.7m/s velocity*

DA GEARS:Tribology Simulation

*Selected sliding conditions: 4.9N load, 2.7m/s velocity

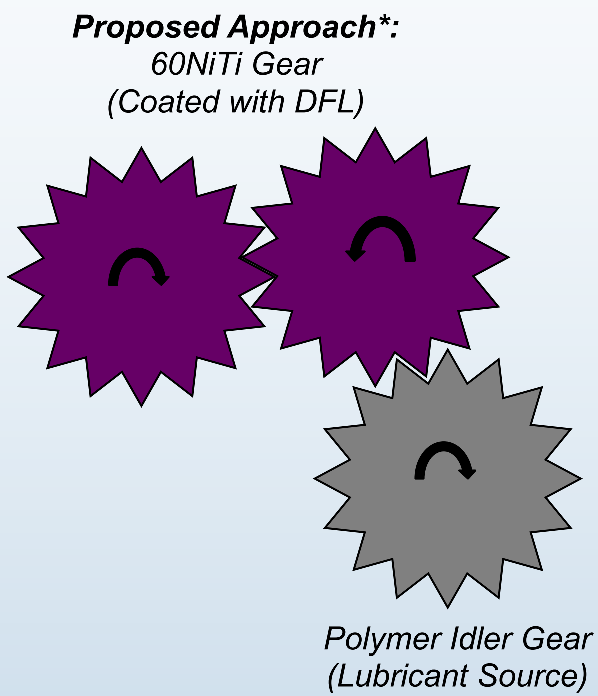
Table I-Test Condition Evaluation-Friction and wear surface appearance (Air at 25°C, 50-60% relative humidity)			
Trial Load (N)	Trial Speed (m/s)	Friction Range	Surface Appearance
4.9	1.35	0.18-0.25	Smooth
4.9	2.70	0.25-0.36	Smooth
9.8	1.35	0.2-0.30	Rough to smooth
9.8	2.70	0.5-0.6	Rough
14.7	1.35	0.5-0.9	Rough
14.7	2.70	0.3-0.5	Rough

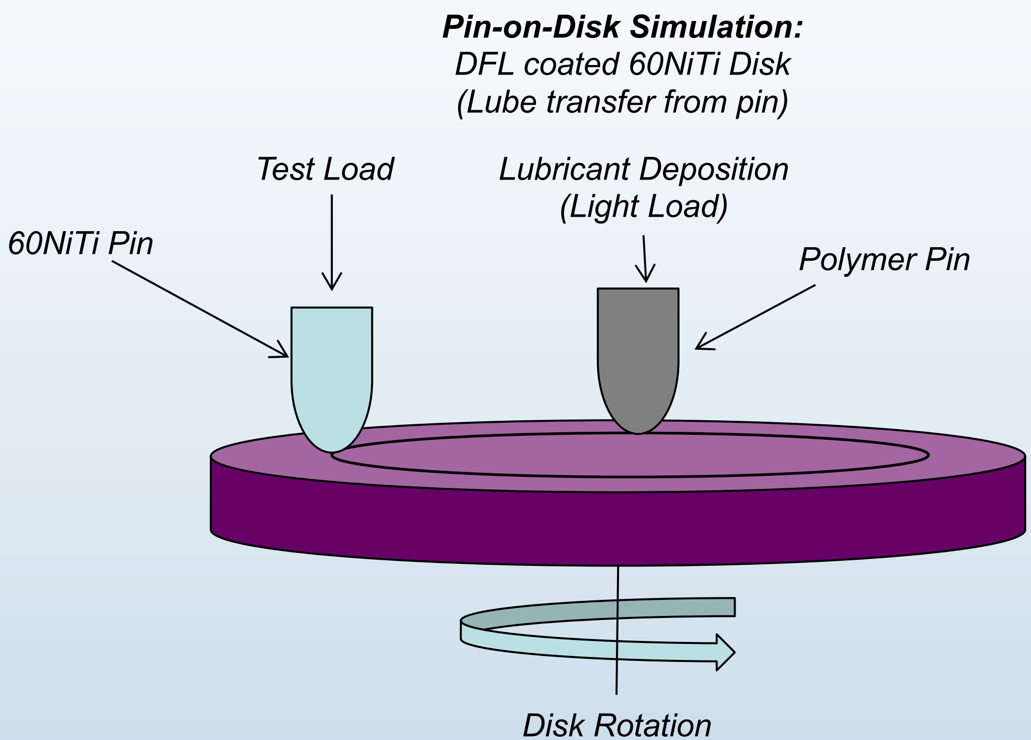


DA GEARS:Tribology Simulation

Transfer Film + Solid Lubrication Concept

- *Similar to bearing lubrication via transfer from the cage.*
- *Technique well described in early space mechanism literature but its current use is largely unknown.*





**Polymer idler gear proposed if DFL life proves inadequate.*

DA GEARS:Tribology Simulation Results

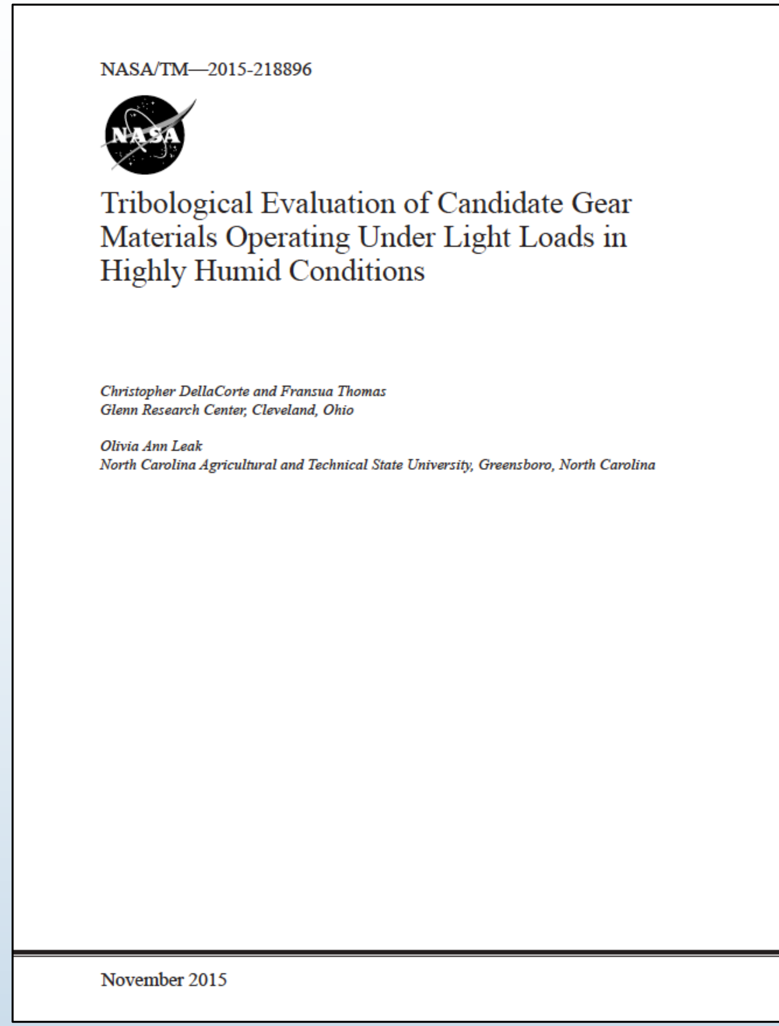
Table II-Friction and Pin Wear Data Summary (Test Conditions: 4.9N load, 2.7m/s sliding speed, air at 25°C)				
Pin Material	Disk Material/Surface Coating	Friction Coefficient	Pin Wear Factor, $mm^3/N\text{-}m$	Surface Appearance
SP21 Polyimide	316L SS	0.29 +/- 0.07	1.9 +/- 0.7 x 10^{-6}	Smooth
SP21 Polyimide	304 SS	0.34 +/- 0.08	0.7 +/- 0.2 x 10^{-6}	Smooth
SP21 Polyimide	60NiTi	0.28 +/- 0.04	2.1 +/- 1.5 x 10^{-6}	Smooth
60NiTi	60NiTi	0.18 +/- 0.03	8.3 +/- 3.2 x 10^{-6}	Rough
60NiTi + SP21	60NiTi	0.15 +/- 0.03	3.1 +/- 1.9 x 10^{-6}	Smooth
60NiTi*	PTFE DFL	0.15 +/- 0.02	184-348 km**	Smooth
60NiTi*	Graphite DFL	0.17 +/- 0.02	24-135 km**	Smooth

**Tests initiated with pre-worn pin (~3mm dia. Wear scar).*
***Tests terminated when DFL wore through to substrate. No additional pin wear was observed.*

Recommendation: 60NiTi gear set with PTFE-based DFL

Information Sharing: Critical Step

- Gears need lubrication.
- Standard lab tests can offer valuable design guidance.
- Applications often come with constraints (e.g., toxicity concerns, life requirements, wet conditions) that limit choices.
- Gov't Report: NASA TM-2015-218896


NASA/TM—2015-218896

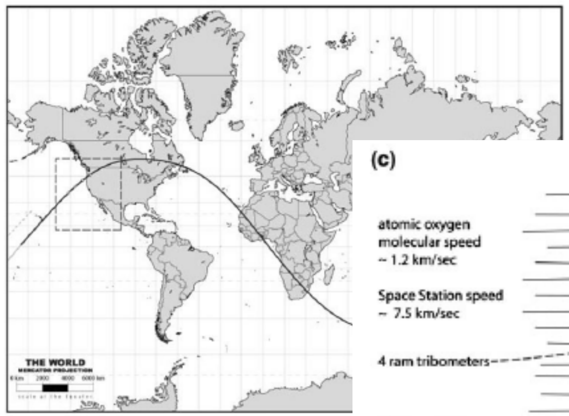
Tribological Evaluation of Candidate Gear Materials Operating Under Light Loads in Highly Humid Conditions

Christopher DellaCorte and Fransua Thomas
Glenn Research Center, Cleveland, Ohio

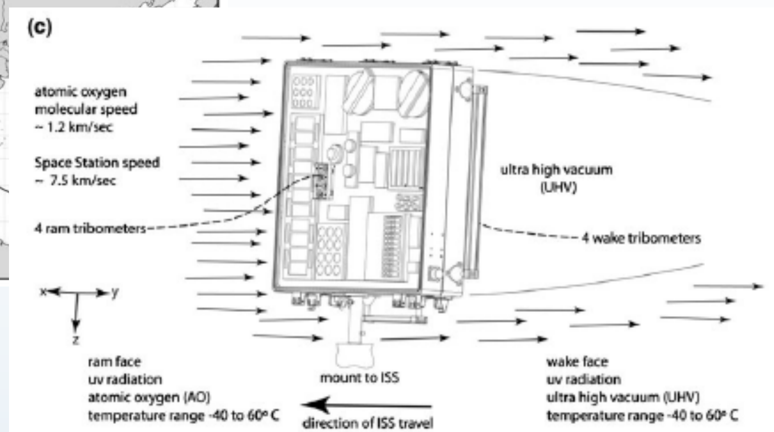
Olivia Ann Leak
North Carolina Agricultural and Technical State University, Greensboro, North Carolina

November 2015

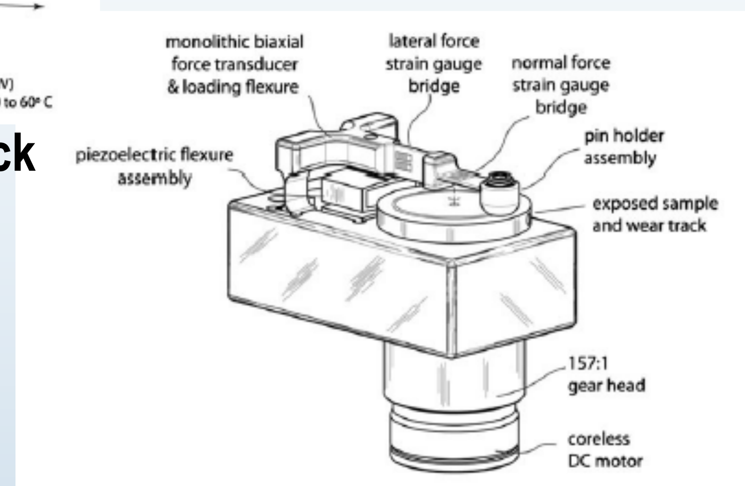
#3-MISSE-7: ISS In-Space R&D



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)

Information Sharing: Everyone Benefits

- In-Space Research and Development
- MISSE experiments help everyone.
- Great first step in developing new space lubricants.
- Excellent student learning opportunities.
- https://www1.grc.nasa.gov/space/iss-research/misse/#misse7
- Open-source paper: Krick & Sawyer, Tribology letters, (2011), vol. 41, pages 303-311

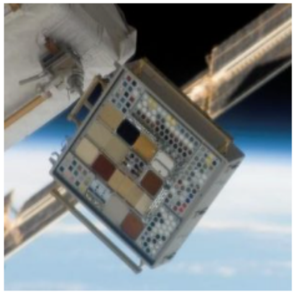
MISSE Experiments

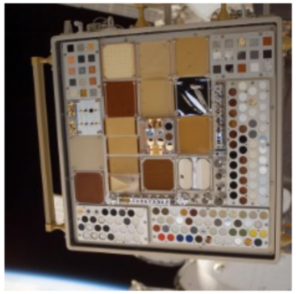

NASA Image: 2002-L-02093 – Closeup image of Tray 1 of MISSE PEC 3 loaded with samples on Earth.


NASA Image: 2002-L-02076 – Closeup image of Tray 2 of MISSE PEC 4 loaded with samples on Earth.


NASA Image ISS013E63407 – MISSE 3 following deployment on the outside of ISS on August 3, 2006.


NASA Image ISS013E63396: Image of MISSE 4 following deployment on the outside of ISS on August 3, 2006.


NASA Image: S116E06941 – This image of the MISSE-3 Passive Experiment Container (PEC) was taken on December 18, 2006. At this point, MISSE-3 has been exposed to the space environment for approximately 4 months.


NASA Image: ISS015E19091 – This image of the MISSE-3 Tray 1 Passive Experiment Container (PEC) was taken in July 2007. At this point, MISSE-3 has been exposed to the space environment for approximately 11 months.

Space Tribology: Summary Remarks

- Space presents many tribology challenges.
- All moving mechanisms and contacting surfaces require purposeful lubrication.
- Lubrication requires something soft in between two hard contacting surfaces.
- Past experience and practice (heritage) provides the best guidance.
- New approaches are often needed for new applications.
- Technology is best matured through careful design, lab testing and space demonstration.

Thank You!


National Aeronautics and Space Administration
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Space Tribology: An Introduction

TAMU Lecture

Dr. Christopher DellaCorte

Senior Technologist, Tribology

NASA

Cleveland, Ohio

<u>TAMU Introduction to Tribology Class</u>
Virtual Lecture
April 8th , 2021