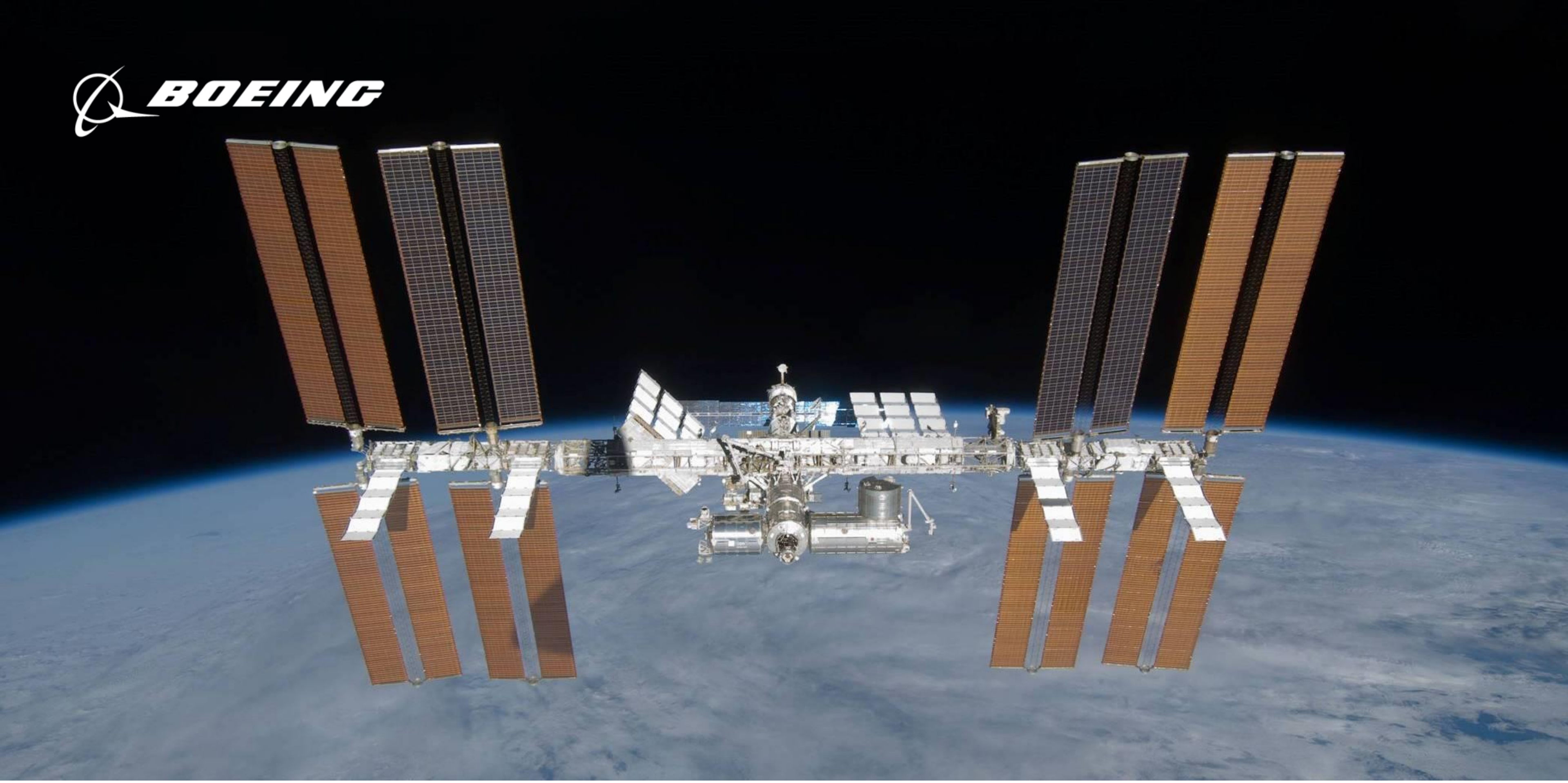
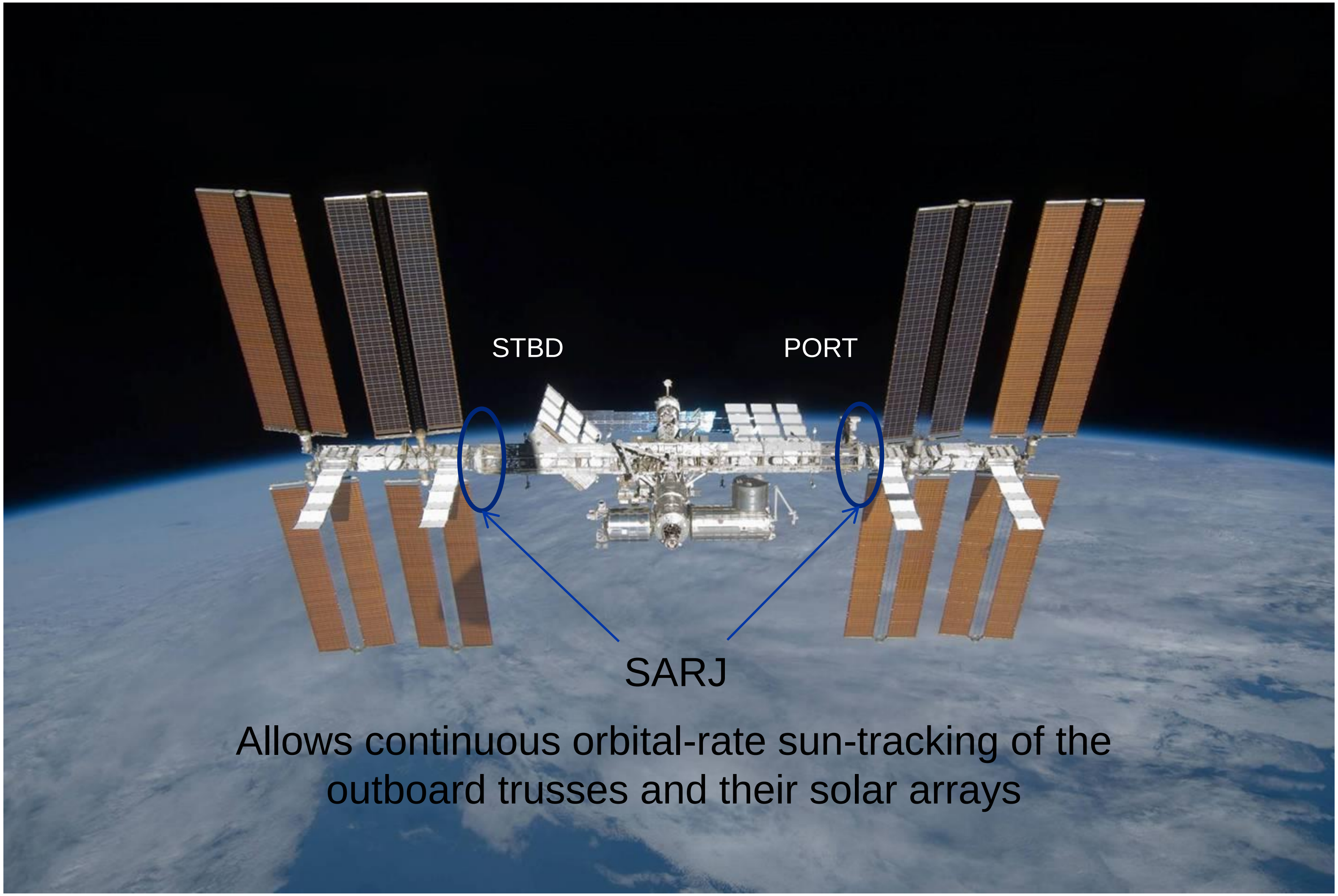


Johnny L. Golden, PhD, SAMPE Fellow
Consultant, Boeing-Retired

SAMPE Long Beach – 2016, May 25th

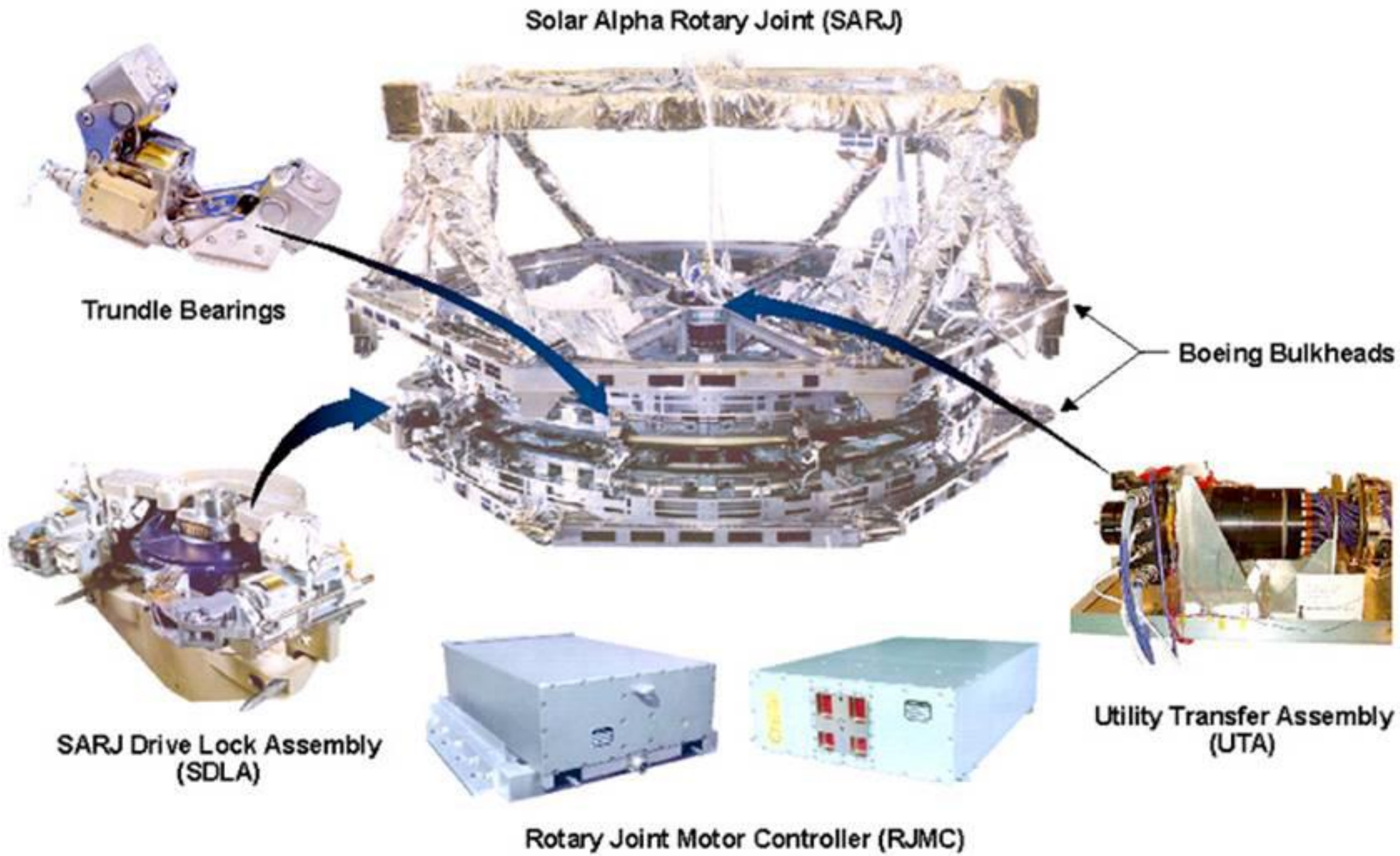
The ISS SARJ: M&P Lessons Learned

INTRODUCTION



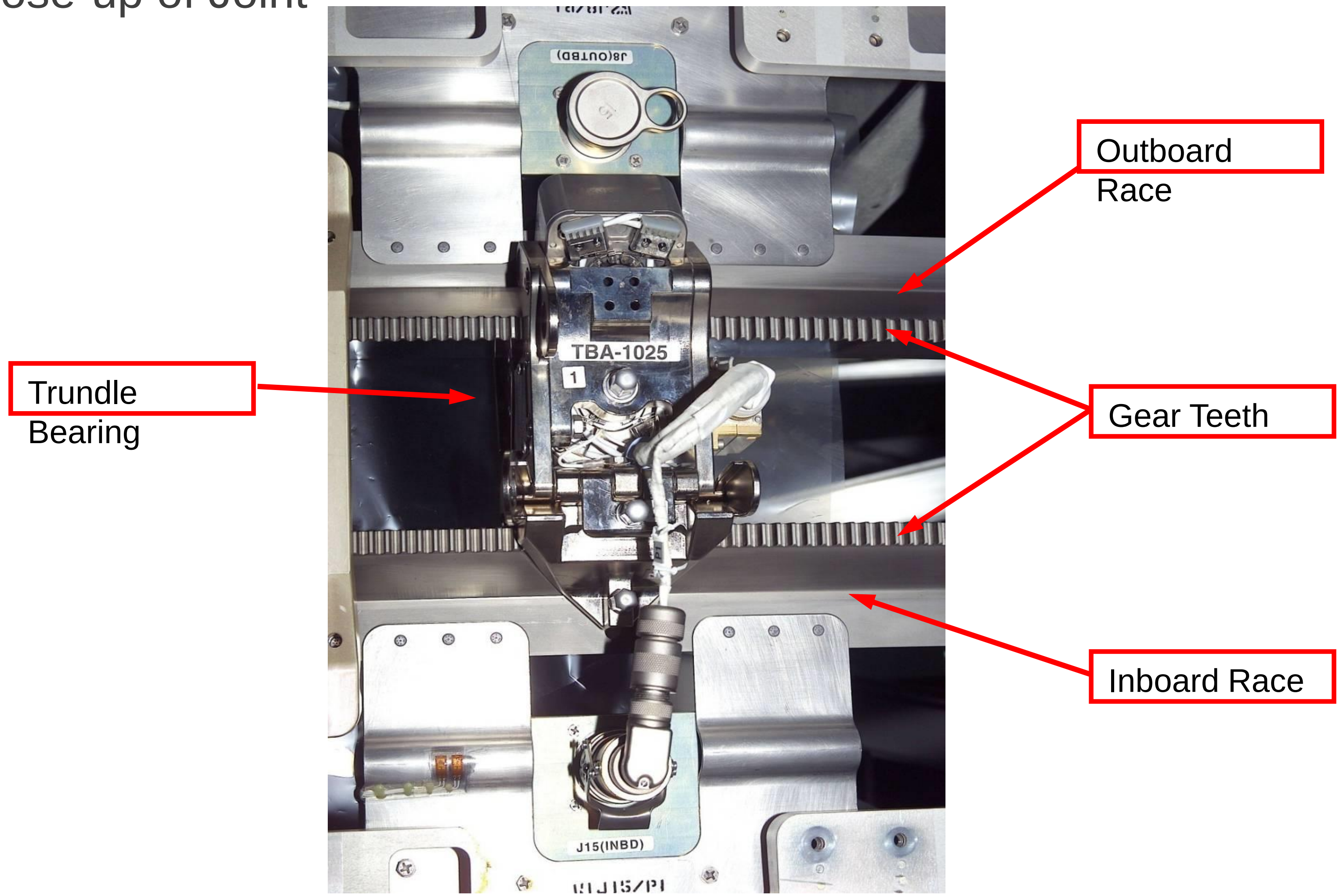
The ISS SARJ: What Is It?

Components



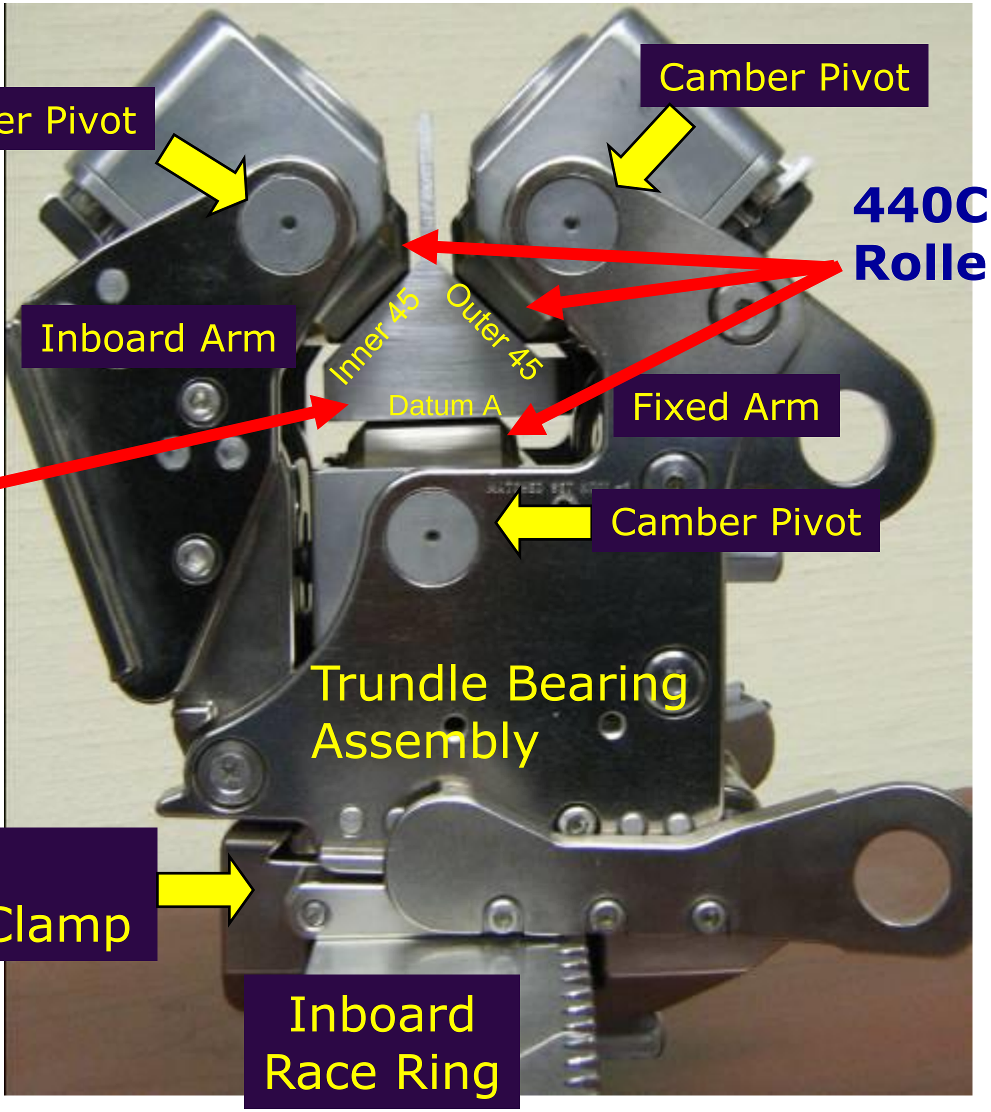
The ISS SARJ: What Is It?

- Close-up of Joint

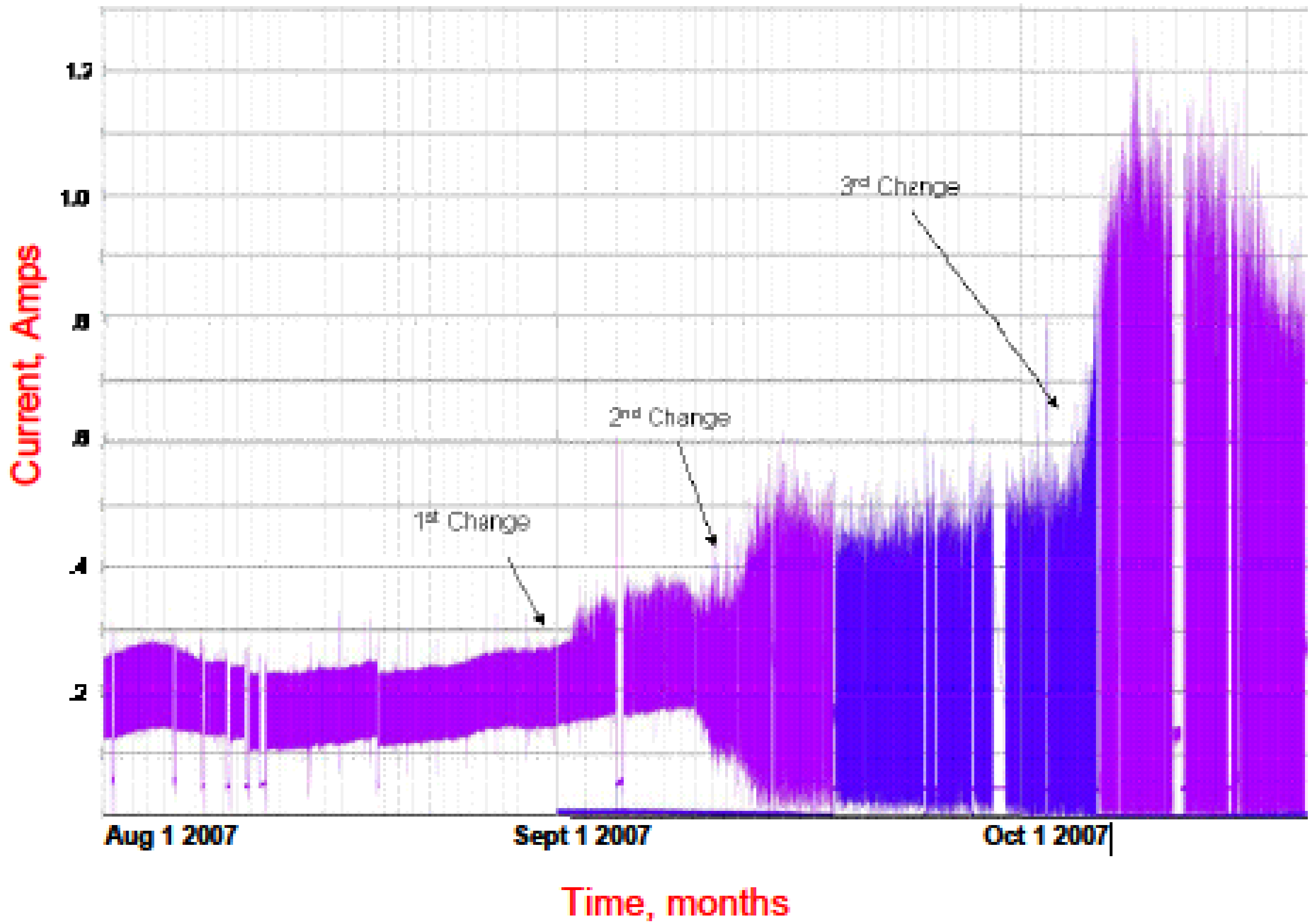


The ISS SARJ: What Is It?

Mechanism Cross-Section

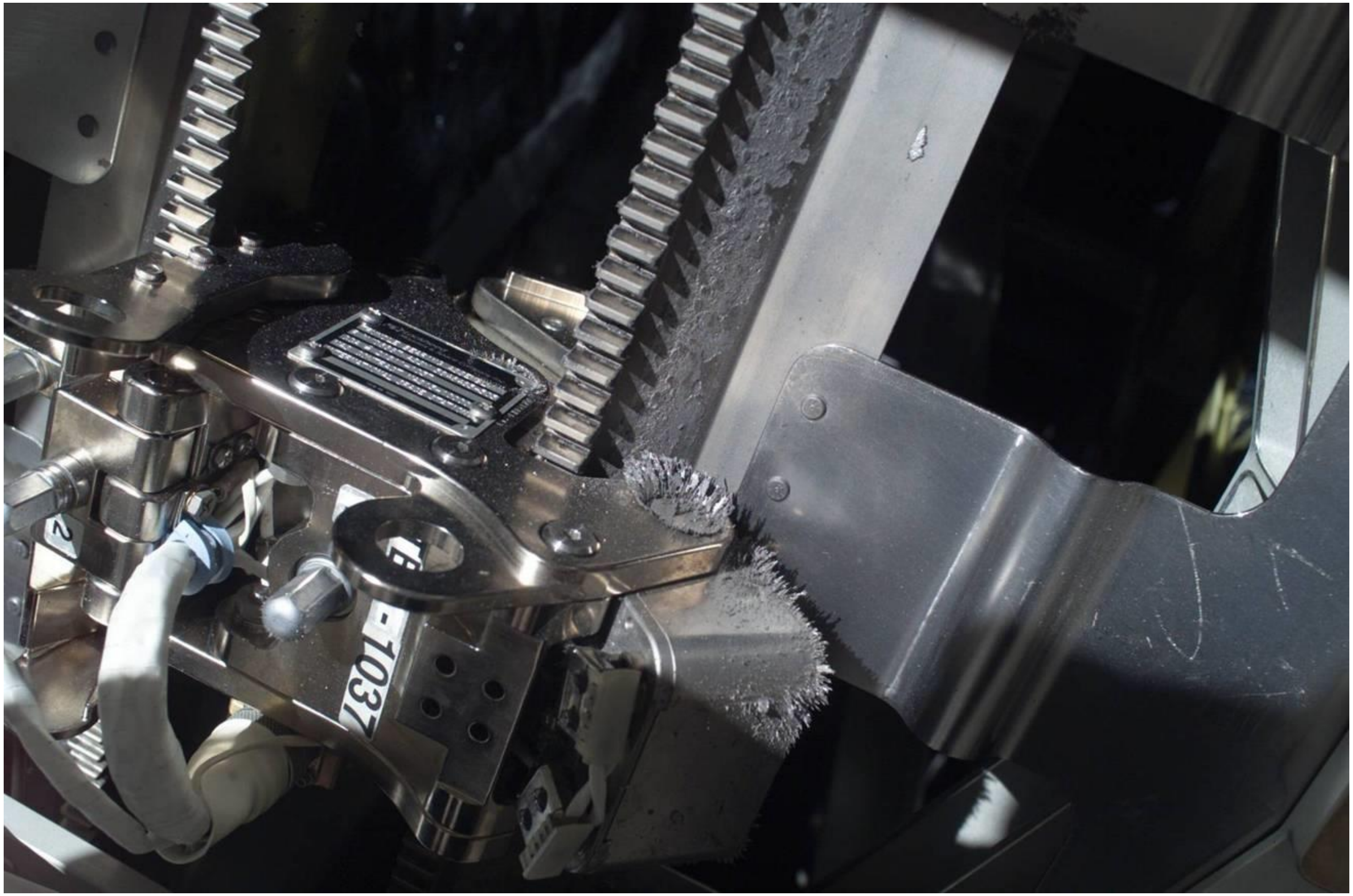


The ISS SARJ: The Anomaly



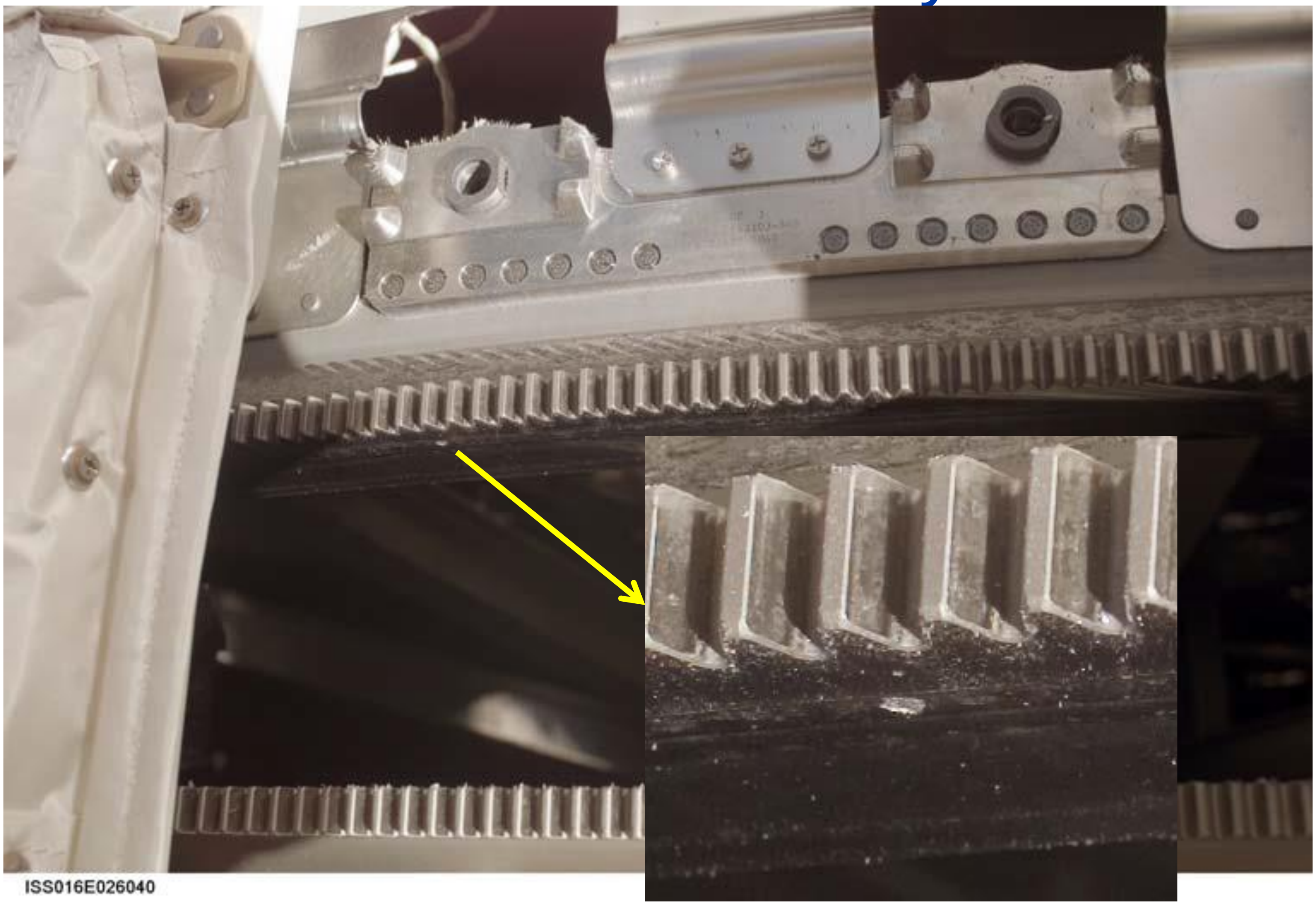
Starboard SARJ Drive Motor Current; Start-up to Failure

The ISS SARJ: The Anomaly



Starboard SARJ Outer Canted Surface Damage and Debris

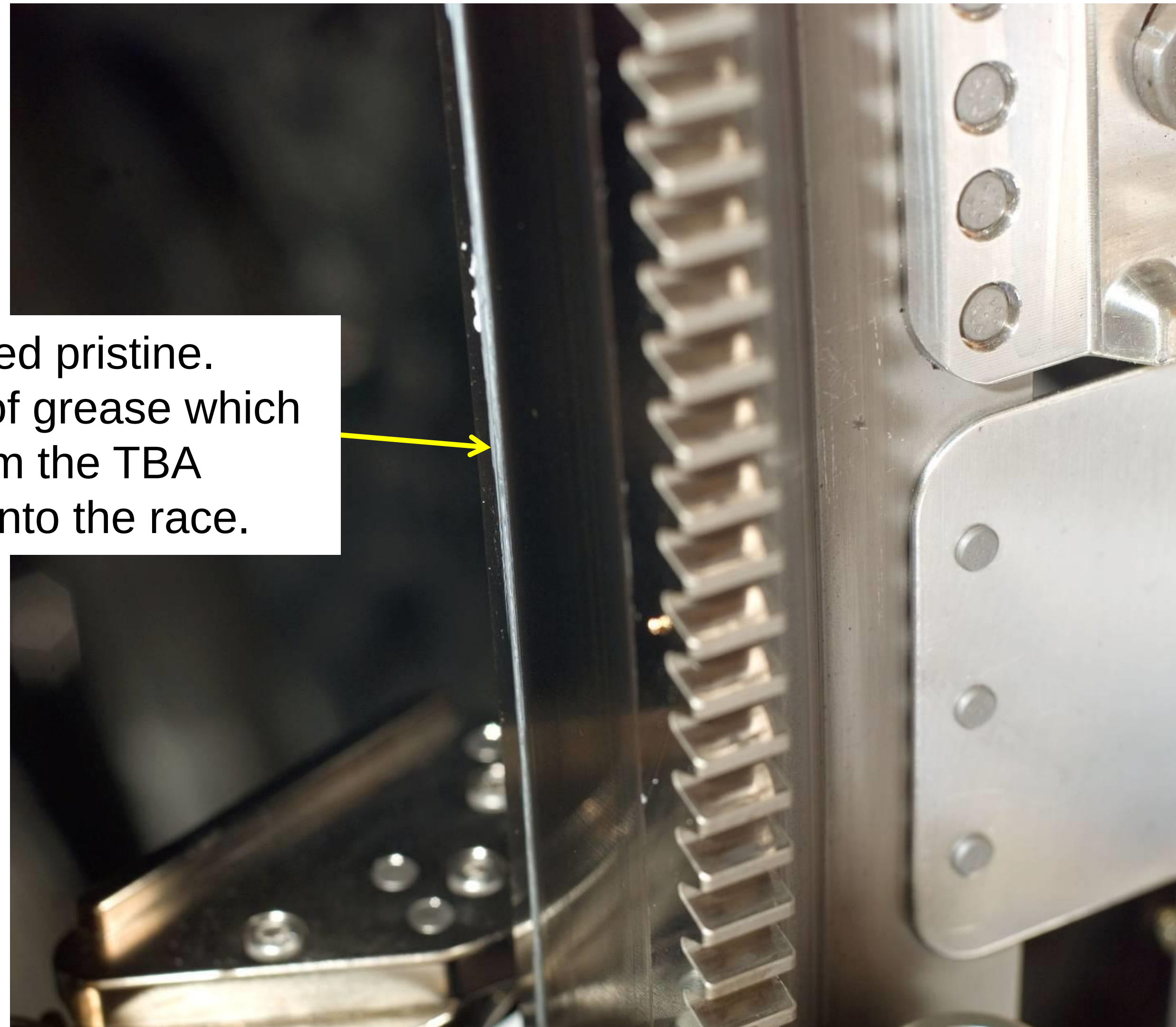
The ISS SARJ: The Anomaly



ISS016E026040

Starboard SARJ Datum A Surface Damage Initiated

The ISS SARJ: The Anomaly



Port SARJ looked pristine.
But note berm of grease which had exuded from the TBA rollers interior onto the race.

The ISS SARJ: STBD Failure Root Cause

- The kinematics of mechanism requires that roller thrust loads be controlled to ensure stable roller line-contact with the race ring surface.
- Inadequate lubrication resulted in stresses within the nitride case and at the case/core interface, instead of within the race ring core.
- These stresses resulted in brittle fracture and spalling of the nitride case.
- Residual magnetic character in spalled fragments caused them to be retained in the mechanism (micro-gravity environment), leading to additional high point-loading events and a cascading failure of most of the nitride layer.

The ISS SARJ: Design Boundary Conditions

- The sole design means of friction control between the race ring and TBA rollers was 1500-2000Å of gold on the rollers.
- Grease would be the typical lubricant for nitrided stainless steels under high-load mechanism conditions.
- A perceived need to avoid grease, reducing contamination potential for EVA crew drove the design approach!
  - This constraint was never documented in the system requirements.
- We saved the Port SARJ and recovered the Starboard SARJ by applying grease to the race ring and allowing the TBAs to distribute it.
  - No one, including EVA Crew Systems, expressed any concerns about the use of grease with the SARJ.

- M&P Lessons Learned
  - Be critical of design approaches which go outside of typical experience.
  - Assure contamination control constraints are documented, with rationale.

The ISS SARJ: The Need for Nitriding

- Nitriding was required to harden the bull-gear teeth for the pinion drive mechanism.
- However, nitriding was also applied to the TBA roller contact surfaces of the race ring, to force mechanical wear within the mechanism to the TBAs (which were designed to be replaceable by EVA).
  - This was done without recognizing that the sole lubrication for the race ring-to-roller contact was now located on a sacrificial surface.
  - Nitriding the roller contact areas of the race ring added significant manufacturing complexity.
  - During starboard SARJ failure, 150 micron surface loss was observed and yet operation was entirely recoverable.

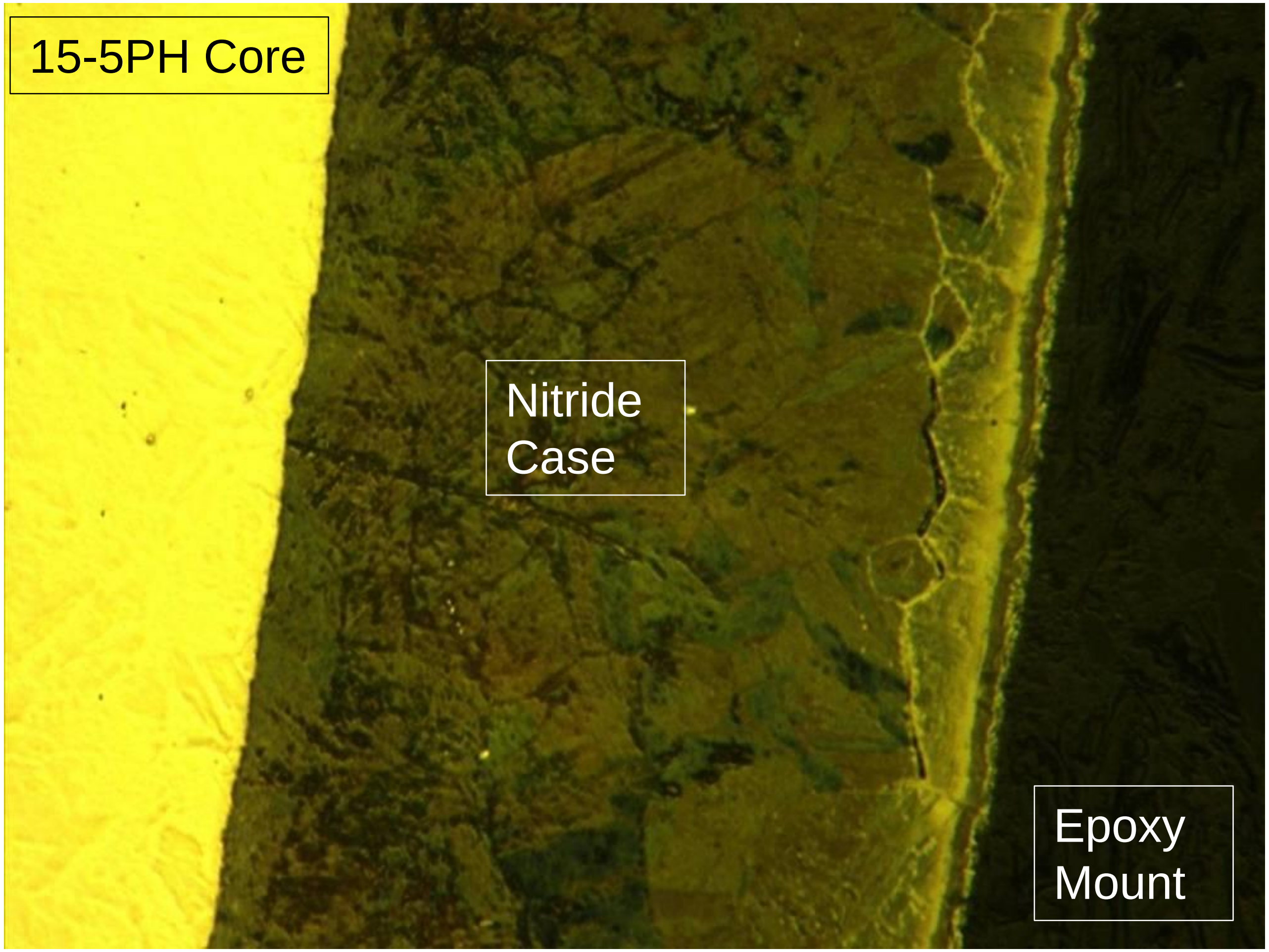
The ISS SARJ: The Need for Nitriding

Nitrided 15-5 PH Fragment from the Starboard SARJ, imaged in cross section. Much of this particle separated at or near the case core interface, and is up to 150 µm (0.006 inch) thick.

- The Starboard SARJ function was recovered, after losing 150 µm (0.006 inch) from the outer canted race ring surface.
- The need for nitriding the race ring is not substantiated, as the mechanism can obviously tolerate a great deal of race ring wear.

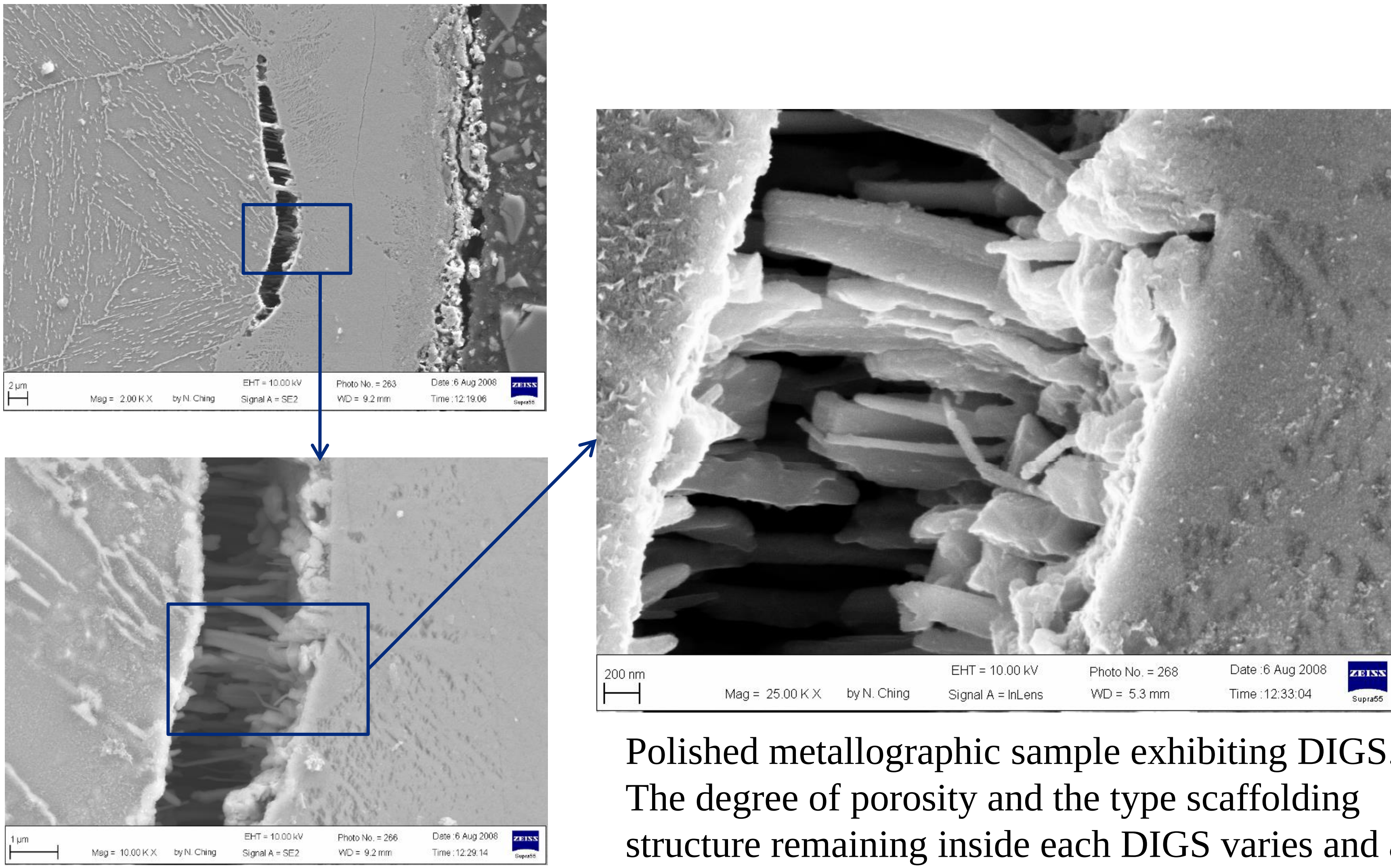
- M&P Lesson Learned
  – Be mindful of the unintended consequences of “make it better” decisions in design.

The ISS SARJ: Quality of the Nitride



Metallographic re-examination of Nitride Control Coupons identified intergranular networking, well in excess of requirements, and the presence of separations.

The ISS SARJ: Discontinuous Intergranular Separations (DIGS)



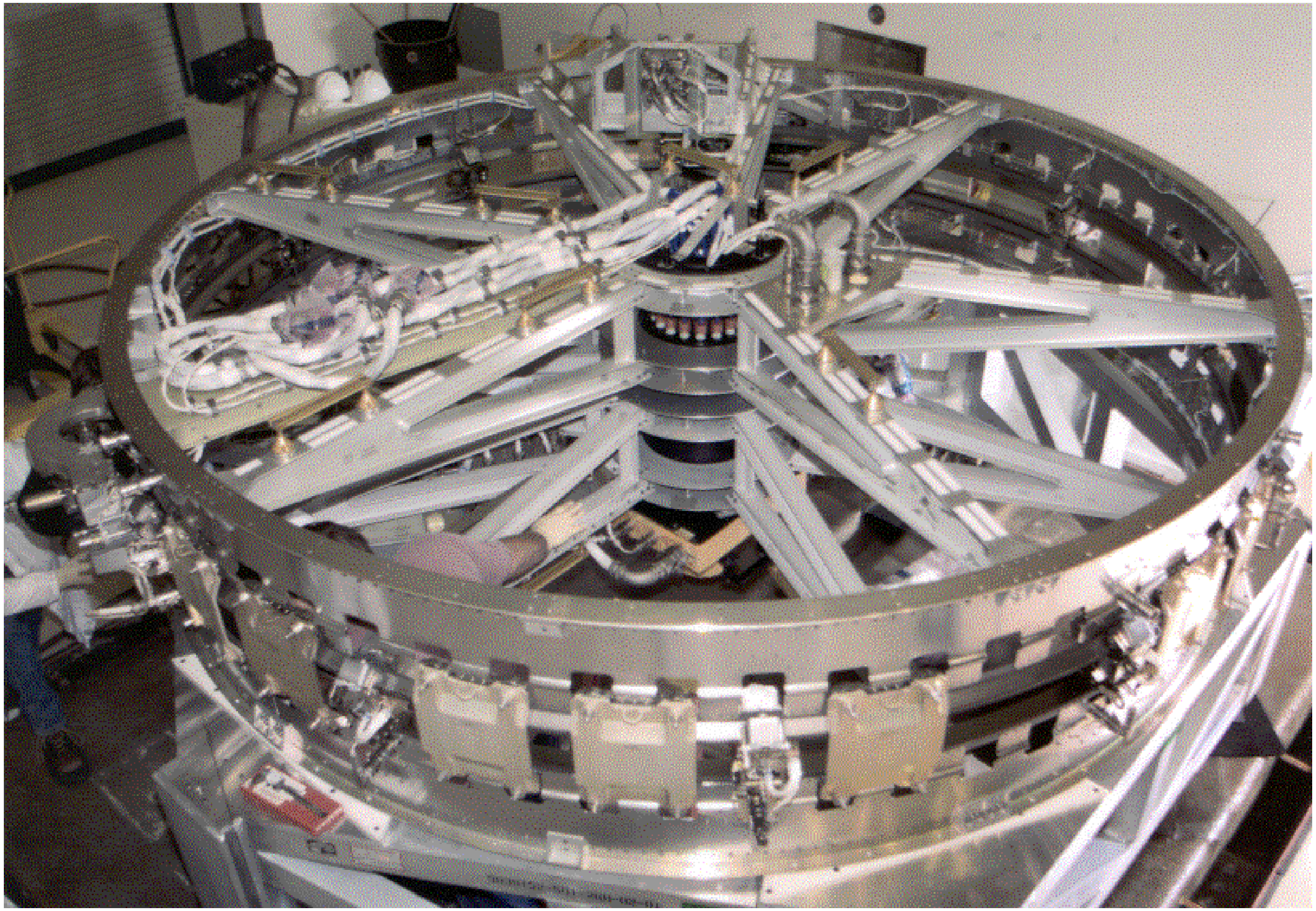
Polished metallographic sample exhibiting DIGS. The degree of porosity and the type scaffolding structure remaining inside each DIGS varies and at times appears as a nanostructure.

The ISS SARJ: Quality of the Nitride

- The original metallographic examination of nitride control coupons, processed with the flight hardware, did not correctly identify the extent of intergranular networking – in excess of engineering control limits.
- Additionally, the coupon examinations did not detect the presence of DIGS.
  - Even though not specifically controlled by engineering, the presence of these crack initiation sites within the nitride structure is an obvious issue.
  - It appears that the DIGS were obscured by the metallographic mounting and polishing technique.

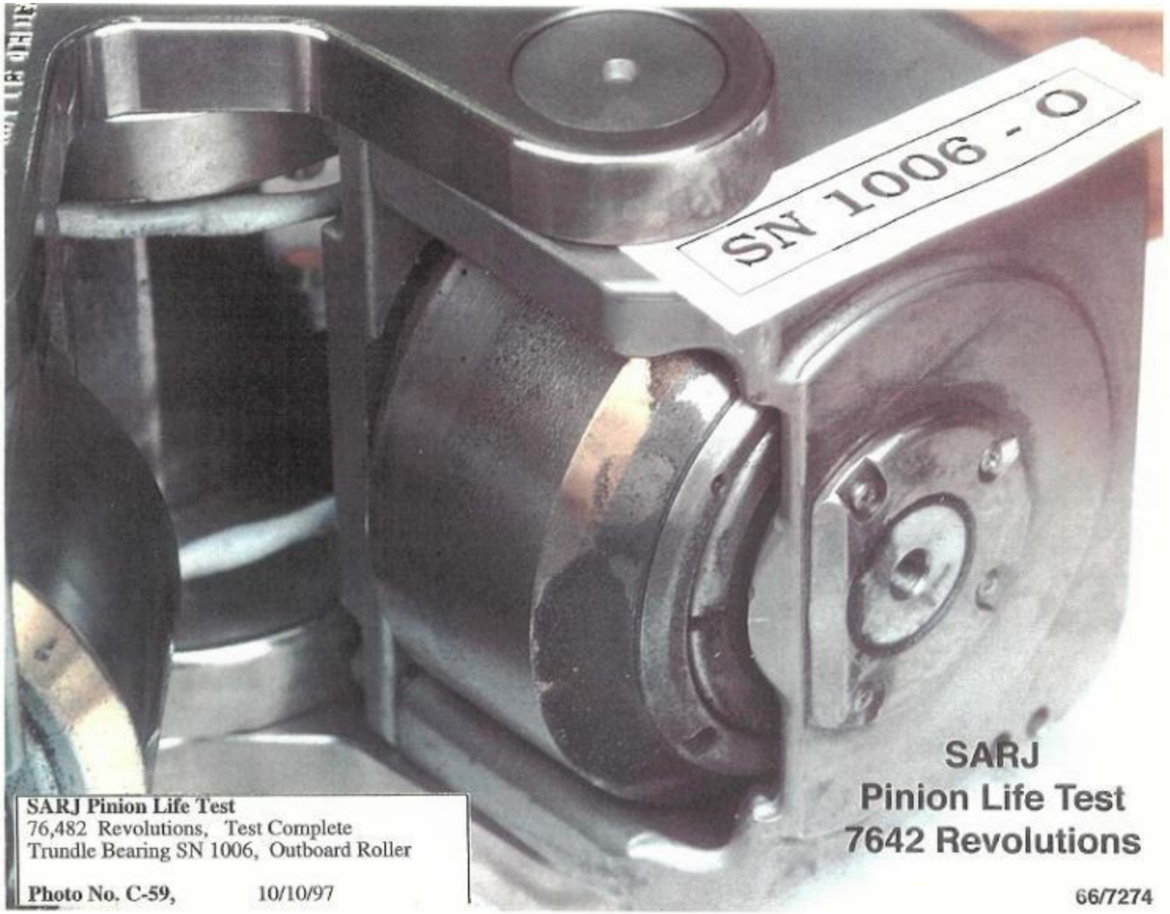
- M&P Lesson Learned
  - Be critical of metallography, and assure that best practices are used to avoid distortion or obscuration of features.

The ISS SARJ: Qualification Test Conditions



- Setting up the Pinion Life Test (PLT), which was also used for TBA/race ring life qualification.

The ISS SARJ: Qualification Test Results



- Post-test inspection of TBA rollers, showing wear debris caked to the roller chamfered edge – suggesting the presence of a conglomerating agent.

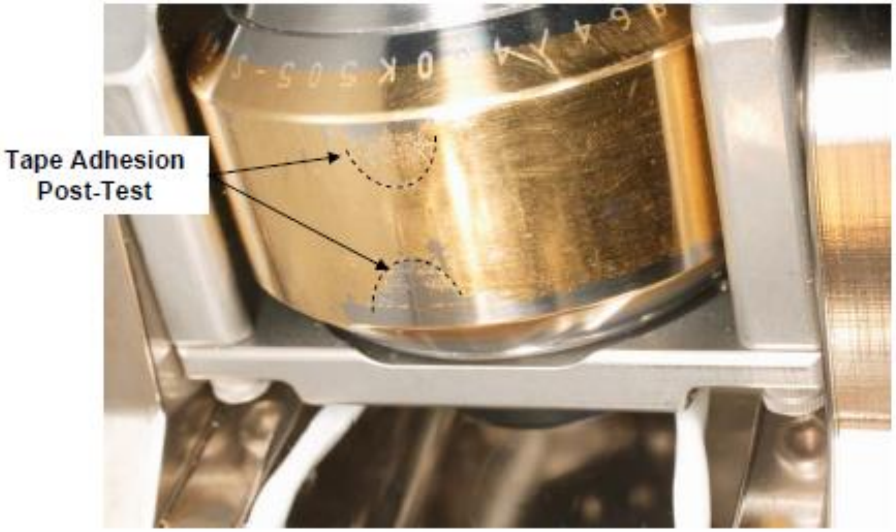
The ISS SARJ: Qualification Testing

- Qualification testing of long-life, complex mechanisms is highly contentious, and expense/schedule will impact the test conditions selected.
  - The ISS PLT was conducted in air and at 186X autotracking speed.
- Post test results indicate that friction was being controlled by inadvertent leakage of oil/grease from within the TBA rollers, but this was not recognized at the time.
- Successful completion of the PLT mislead the system managers.

- M&P Lessons Learned
  – Bring critical thinking to the decision process for determination of qualification testing conditions.
  – Assess the qualification test results closely, looking for artifacts induced by the conditions of test.

The ISS SARJ: Hardware Storage Controls

- Flight TBA roller with gold loss, accepted as-is, based on the successful PLT test.

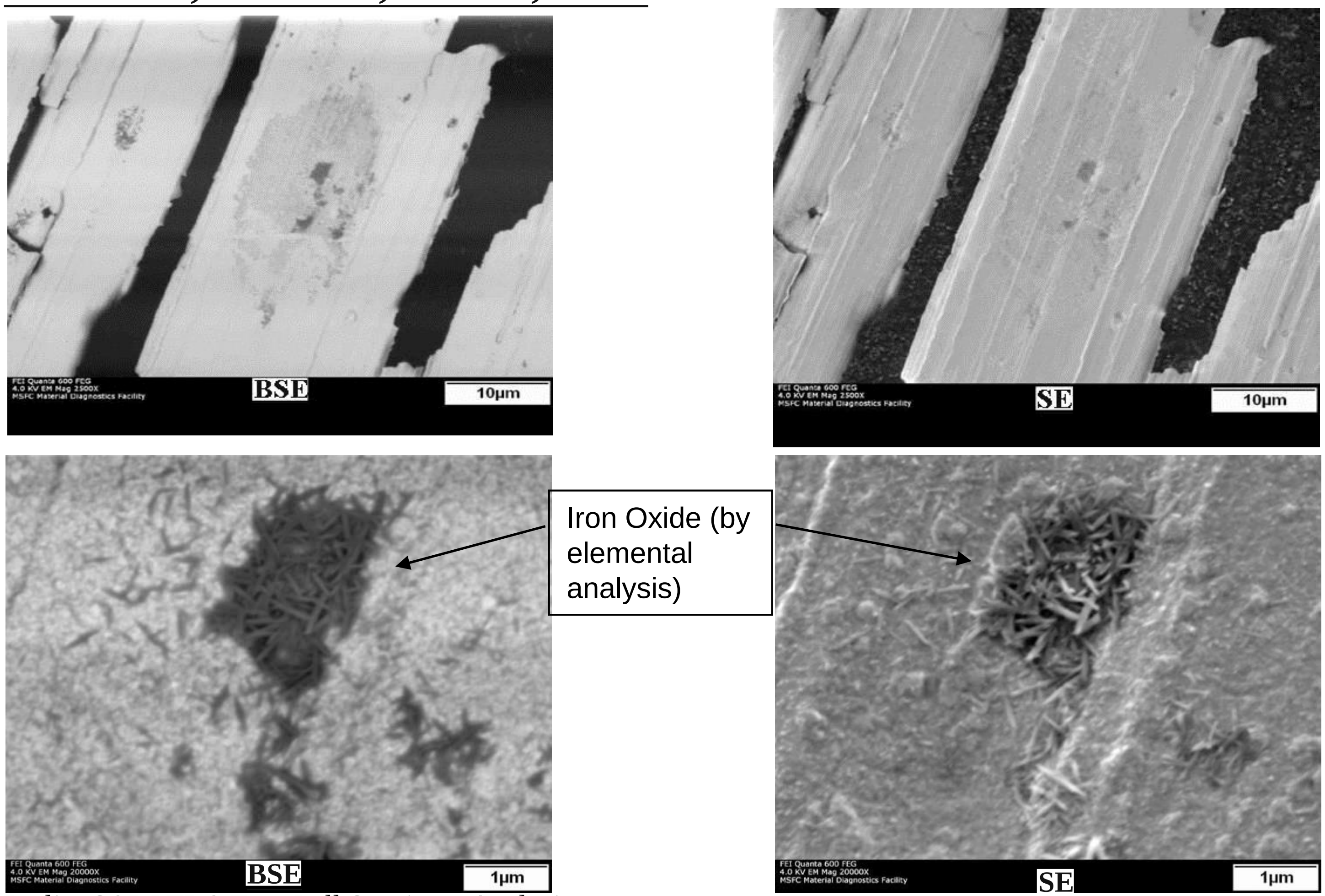


- Flight spare TBA roller with gold loss, and additional gold loss as a result of carbon tape testing.
- The gold surfaces where the adhesion failed were examined by SEM, shown on next slide.

The ISS SARJ: Gold Adhesion Loss

NASA MSFC EM30 Material Diagnostics Team

TBA 1005, Outer 45, Test #1, SEM



Prelim SARJ TBA Tape Pull Specimen Analysis

The ISS SARJ: Hardware Storage Controls

- It was demonstrated that the 440C roller surfaces re-oxidize with time under normal terrestrial conditions, undercutting the gold coating and causing complete loss of adhesion.
- Although adhesion loss on rollers was observed on hardware preflight, the successful PLT test (where no gold remained on roller surfaces) was used to accept the condition.
- It was not recognized that gold adhesion was critical to friction control in the mechanism during flight.

- M&P Lessons Learned
  - Spacecraft hardware must often be designed considering the terrestrial environment, in addition to the space environment.
    - Consider a more robust approach to accommodate the ground environment or the exposure to unexpected conditions.
  - Look for finishes sensitivity, which may require environmental controls.

The ISS SARJ: M&P Lessons Learned

- SUMMARY
  - Robustness of Design in Lubricated Systems
    - Difficult to quantify;
    - Typically increases cost;
    - Easier said than done!
  - First choice in lubrication approach should be within typical experience for the materials and loads involved.
    - If not, insist the program/system document why.
  - Participate in the definition of system life test conditions and look hard at the results.

  - Learn from our hard lessons.

The ISS SARJ: M&P Lessons Learned

ACKNOWLEDGEMENTS

- All Boeing and subcontractor work performed under the NAS15-10000 contract, ISS Integration & Operations
- All photography courtesy of NASA
- SARJ Anomaly Team
  - NASA Johnson Space Center
  - NASA Kennedy Space Center
  - NASA Marshall Space Flight Center
  - NASA Goddard Space Flight Center
  - NASA Glenn Research Center
  - NASA Engineering and Safety Center (NESC)
  - The Boeing Company
  - Lockheed-Martin Space Systems
  - ATK Space Systems
  - Purdue University
- D684-13412, ISS SARJ Anomaly Report