AEROSPACE REPORT NO.
ATR-2011(5389)-1

Recommended Supplier Surveillance Practices and Independent Verification for Reaction Wheel Procurements

January 31, 2011

Luke A. Rinard[1], Erin L. Chapman[1], David J. Carré[2], Michael R. Hilton[3], and Peter P. Frantz[2]

[1]Electromechanical Control Department, Vehicle Systems Division
[2]Micro/Nano Technology Department, Physical Sciences Laboratories
[3]Mechanical Systems Department, Vehicle Systems Division

Prepared for:

NASA Marshall Space Flight Center's Chief Engineer Office
National Space Science and Technology Center
320 Sparkman Drive
Huntsville, AL 35805

Contract No. NNM07AA96C

Authorized by: Civil and Commercial Operations

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Approved by:

Dr. Walter H. Chung, Director
Electromechanical Control Department
Guidance and Control Subdivision
Vehicle Systems Division
Engineering and Technology Group

Debra L. Emmons, Assistant Principal Director
Program Development
NASA Programs Division
Civil and Commercial Operations

Abstract

Reaction wheel issues can cause lengthy schedule delays and cost overruns during procurement. Reaction wheel anomalies can be mission-ending. In order to mitigate risks, NASA's Discovery, New Frontiers, and Lunar Quest Program Office contracted with The Aerospace Corporation to provide a document listing recommended supplier surveillance practices including recommended inspection points during fabrication and testing. The document is to assist in the procurement of reaction wheels and provides a general description of reaction wheels and their key components, as well as reaction wheel design considerations. A concluding section describes typical reaction wheel anomalies.

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1. Abstract

Reaction wheel issues can cause lengthy schedule delays and cost overruns during procurement. Reaction wheel anomalies can be mission-ending. In order to mitigate risks, NASA's Discovery, New Frontiers, and Lunar Quest Program Office contracted with The Aerospace Corporation (Aerospace) to provide a document listing recommended supplier surveillance practices including recommended inspection points during fabrication and testing. The document is to assist in the procurement of reaction wheels and provides a general description of reaction wheels and their key components, as well as reaction wheel design considerations. A concluding section describes typical reaction wheel anomalies.

2. Reaction Wheel Overview

Reaction wheels are used for active stabilization and control of a spacecraft. They require the use of spacecraft power and electrical commands, but do not require propellant. Figure 1 shows a cross sectional view of a typical reaction wheel assembly (RWA), showing its various working parts, which include bearings, a rotor, a motor, and control and power electronics. On the axis of the RWA's motor is an inertia rotor, or flywheel. The flywheel changes speed to absorb angular momentum imparted on the spacecraft from external torques. Examples of external torques include atmospheric drag and solar pressure.

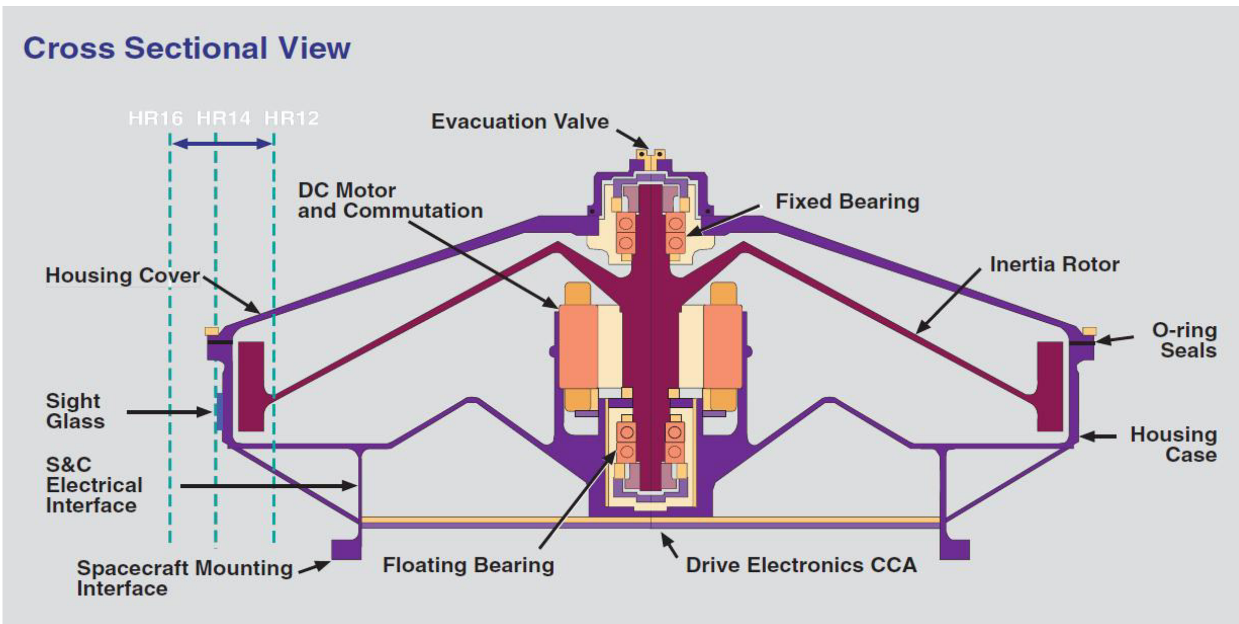

Figure 1. Honeywell Constellation Series Cross Section (Image courtesy of Honeywell International).

2.1 Bearings

The bearings on an RWA allow constrained relative motion between the rotor and motor. Bearings (Figure 2) consist of an external and internal race, rolling elements (balls or rollers), and a separator/cage. The external race is a ring with an inside groove in which the balls roll and slide. The inner race is a ring with an external groove in which these same balls roll and slide. The separator or cage is a ring with a number of holes or pockets equal to the number of balls in the bearing. The holes are slightly larger in diameter than the balls to accommodate free rolling by keeping the balls from contacting each other. Some bearings have built-in shields to prevent contaminants from entering the races, but this is not typically done for RWAs.

Bearings are designed to operate with lubricant between the rolling elements and races to produce a hydrodynamic effect that keeps these pieces separated by a film barrier. This prevents metal-to-metal contact that could damage the rolling elements. It is important to note that speed is a factor in maintaining the hydrodynamic effect. Slow speed can result in no lift off and metal-to-metal contact. There are bearings that operate in this regime, which is referred to as "boundary lubrication," but this is not conducive to long life.

Figure 2. Typical Ball Bearing (Image courtesy of Wikimedia Commons).

2.2 Motor

One of the most common types of motors used in RWAs is the brushless DC (BLDC) motor. BLDC motors are composed of a rotating portion called the rotor, on which permanent magnets are mounted, and a stationary part, called the stator, that houses the windings. Running current through the stator windings creates a magnetic field that can be rotated to pull the rotor in either direction at a wide range of speeds. Typically, BLDC motors have two or three sets of windings evenly spaced around the rotor (referred to as 2-phase and 3-phase motors, respectively). For redundancy, additional sets of windings can be included.

Figure 3. Stator of a Two-Phase BLDC Motor. (Image courtesy of Wikimedia Commons).

2.3 Electronics

RWA electronics include all of the control electronics, power elements, and harnesses. Common RWA electronics components consist of wheel speed sensors, motor current sensors, motor speed controllers, bus interface components and harnesses. Different RWA configurations have electronics enclosed in the rotor housing or in a separate enclosure. Also, the electronics can have any combination of analog or digital interfaces depending on the satellite's configuration. Electronics that are inside the evacuated wheel housing have been shown to exhibit outgassing that can raise the housing internal pressure to levels that are unacceptable.

Figure 4. Reaction Wheel Electronics (Image courtesy of Surrey Satellite Technology).

3. Design Considerations

Design considerations are presented for each RWA component. Specific recommendations are highlighted throughout the text in ***bold/italic.***

3.1 Motors

Use three phase motors as they can be operated with only two phases in case one phase fails.

3.2 Electronics

RWA electronics can suffer from the same issues as other space quality electronics. For instance, RWAs are vulnerable to a supply chain for electronic components that is continually changing. It is, therefore, important to buy all of the needed components at the same time. A second buy will inevitably require some level of re-qualification, driving up overall cost. Similarly, when procuring wheels for individual spacecraft, it is important to understand whether electronic components used in previous procurements are still available and if these parts were procured using standards acceptable to the program. If new electronics must be used, then the project may take on increased qualification costs or may have to accept increased risk. Another recurrent issue is the use of Class S versus upscreened components. Class S refers to parts that satisfy requirements for space electronics defined in MIL-STD-883 [1]. They are more expensive, but more reliable than parts that do not meet this standard. Upscreening refers to a number of strategies for qualifying microcircuits that are not built to Class S requirements, usually through increased testing.

Radiation tolerance requirements for the mission are another factor to consider. To ensure that electronics will work properly throughout the duration of the mission, subject matter experts (SMEs) need to be consulted to determine the level of radiation hardness required for the mission, and RWA electronics should be built to that specification.

3.3 Bearings

Spin bearings are one of the most critical components of an RWA and one of the most challenging problems in tribology for the space industry. Bearings are built to tight tolerances in order to reduce jitter to the space vehicle and to maintain wheel balance. The lubricant must be carefully chosen and must be free from contaminants. Real time life testing is required to validate changes in bearing design.

RWA manufacturers along with bearing suppliers and Aerospace have developed the technology, tools, and practices to provide long life performance. Aerospace has developed specialized bearing analysis tools, materials, and chemical tests over the years that have been used by various vendors. These tests are still executed by Aerospace for validation. Bearings are very sensitive to subtle changes in processing, so testing must be executed after each change to assure continued quality.

The following factors should be considered in the design of RWA spin bearings.

3.3.1 Materials

RWA bearing balls and rings are made from a wide variety of materials, with advantages and disadvantages to each. Some examples are: 52100 steel, 440C steel, silicon nitride (balls), and CRU20 steel. Steels are generally more ductile than ceramics, but do not stand up well to high temperatures. Ceramics are generally stronger and more heat tolerant, but can crack if subjected to excessive stresses such as those as seen at launch.

For cages, phenolic is the most common material. It has a long history, but it is a heterogeneous material that has differences from lot-to-lot and between manufacturers. Polyimide is less common, but has been used successfully in space applications. Stamped steel may still be used in some designs, but is generally not associated with long life. Retainerless bearings have been proposed by some, but are not known to have flight heritage in RWAs. There are some attractive benefits to a retainerless design, but it creates the potential for clustering of the balls which can induce vibration. Also, there are currently no precise computational techniques for analyzing bearing loads and dynamics for retainerless designs. ***Unless there is a strong motivator for change, heritage materials should be used, as changing materials can introduce unknown risks.***

3.3.2 Geometry

Generally, a smaller bearing is desirable to minimize bearing drag torque and power, but the bearing size must be large enough to reduce stresses to below the yield limit during launch. Launch load requirements are dictated by wheel mass and momentum requirements. Rolling contact fatigue does not generally drive the bearing size selection for RWAs.

RWAs usually have pairs of bearings bolted together which are generally not axially symmetric, but have distinct front and back sides. These bearings can be arranged back-to-back, front-to-front, or back-to-front. Back-to-back provides greater moment rigidity and is more tolerant of rotor thermal excursions. Face-to-face mounting is more tolerant of misalignment. Both arrangements are used in RWAs. Most, but not all, RWA bearings are operated with rotating inner ring and a stationary outer ring. ***The bearing mount shoulder must not extend beyond the height of the raceway bottom (Figure 5).***

Race curvature is the ratio between the raceway radius and ball diameter (Figure 5). ***The standard minimum race curvature is 51.6%; exceeding this value is not recommended.*** A tighter curvature (higher than 51.6%) may aggravate bearing sensitivities such as ball-speed variations, geometric imperfections, and kinematic starvation. If the curvature is too loose, however, the bearing may have insufficient static capacity.

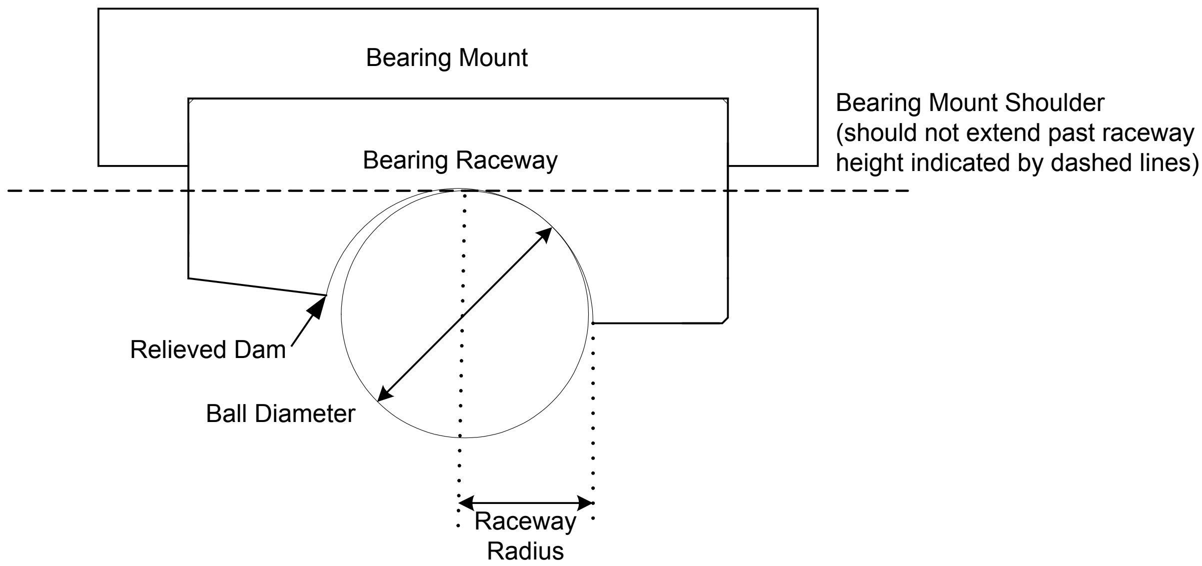

Figure 5. Angular Contact Ball Bearing Cross Section.

3.3.3 Preload

RWA ball bearings must be preloaded for proper operation. Preload increases rigidity, helps to limit vibration, and increases traction which helps to maintain proper ball kinematics. Excessive preload causes higher contact stress at the ball/race interface, resulting in accelerated lube and race wear. Conversely, inadequate preload raises the risk of having insufficient traction to maintain proper ball kinematics which may result in sliding. Preload typically decreases with life -- springs and flexures tend to lose tension with time, or at least exhibit an increase in hysteresis -- so one must consider both beginning and end of life requirements. ***An estimate of the anticipated relaxation based on material analysis as well as heritage performance should be provided during the design phase, and maintenance of sufficient preload until end-of-life should be ensured.***

A smaller preload is desired to minimize bearing drag torque and lubricant degradation. However, the preload must be applied such that the design does not unload at the highest expected operating temperature (with margin).

Insufficient clamping and/or preload force can result in the rotation of bearing races in their housing. ***The frequency of rotation should be predicted from a harmonic-drive analysis of the clearances between the ring and housing and the rotor frequency.*** This rotation can result in unacceptable wear and debris. It may be more prevalent at high speeds and low temperature. If conditions are right, it typically begins during initial testing and can only be detected by physical inspections after sufficient damage has been done to cause performance problems.

Fretting is material wear that occurs at the contact area between two materials under load and subject to some relative motion. Fretting at any interface between moving parts in the preload compensation mechanism should be avoided. This may occur, for example, at the interface between an outer ring and the cartridge in which it floats (this cartridge allows axial movement as the shaft expands and contracts with temperature). Such damage can lead to seizure of the ring in the housing, resulting in excess or insufficient preload and rapid bearing failure. ***Ensure uniform spring force, minimal radial force, and minimal moment loads on the axially moving component to mitigate risk of fretting.***

Avoiding the use of similar materials on both sides of interface is recommended as well. Dissimilar materials tend to fret more slowly than similar materials.

3.3.4 Lubricant

Adoption of synthetic lubricants has generally increased expectations for bearing life. Rheolube greases formulated by Nye Lubricants using synthetic Pennzane oil are common in space applications. Currently, grease is slightly preferred over oil as it is believed that the thickener acts as a reservoir of oil until it is drawn by capillary action into the critical interfaces. Grease can take months to fully run-in, and will have thicker film thickness until then.

If oil is used, it may be resupplied from a reservoir through active or passive mechanisms. Passive oilers are usually designed to provide oil at a continuous rate, while active oilers are generally used for contingencies (to address torque spikes or rising torque). Because both approaches usually have a complex design with many critical components, they do not have high reliability. Some attitude control wheels are given a single charge of oil at beginning of life. These generally have a wider distribution in lifetimes than those with grease or oilers.

Avoid perfluoropolyether (PFPE) and silicone lubricants, particularly for low-speed operation. PFPEs are fluorinated lubricants that tend to react with metallic surfaces under boundary conditions (below elastohydrodynamic (EHD) lift-off speeds) to produce a crusty tribopolymer material, often referred to as "brown sugar," that can cause significant bearing damage. PFPEs are very common in space systems because they work well at low temperatures and have a very low vapor pressure. They are good for low cycle and/or low loaded applications, but not for RWAs. Silicone lubricants have very little space heritage. While their use has been promoted by some, they should be considered experimental in RWAs. They are also incompatible with hydrocarbon lubes and coatings, so cross-contamination with other materials would be a concern as well.

Eventual lubricant starvation is inevitable for any mechanism without an active resupply system. The time course to this starvation is highly variable and generally not predictable beyond the ability to calculate lubricant loss by evaporation. Any assertion that any other lubricant loss rate mechanism can be estimated should be viewed with skepticism. Lubricant loss mechanisms are rarely the cause for early-life performance anomalies, but can promote the onset of normal end-of-life processes if they are not taken into account and minimized.

Lubricant additives are used to provide a variety of effects, including anti-wear and extreme pressure resistance. ***High molecular weight anti-wear additives such as tricresyl phosphate and Syn-O-As 8478 have low evaporation rates and are recommended for use in RWAs. Chemical analysis of lubricant after qualification/acceptance testing is recommended to ensure that additives have not been consumed and that no significant evaporation or degradation of the lube has occurred.***

Bearings sometimes have shields and/or seals to protect the bearing and prevent contamination; however, shields on attitude control wheel bearings are unusual, and are generally considered an unnecessary source of potential complications. Conventional seals should be avoided. Ball bearing assemblies often have a small clearance between the shaft and housing. This does not create a true seal, but it acts as a partial seal commonly referred to as a “labyrinth seal” that can significantly reduce oil evaporation and contamination.

4. Procurement Guidelines

This section discusses RWA acquisitions and provides recommendations. An underlying theme throughout is the need for consistent oversight throughout the procurement cycle and the use of accepted standards for parts selection and program management review. This level of vigilance will increase costs, but will decrease risk which can reduce costs in the long run if it prevents problems from occurring.

4.1 Procurement Process Outline

The requirements for the RWA should reflect the program needs and not simply parrot the vendor's standard specification. Every deviation from the standard specification will incur additional costs, but it is far better to bring these to light at the beginning of a procurement rather than later. Changes made later in the process will be more expensive and may result in schedule delays as well. This is why all requirements should be included in the initial request for quotation (RFQ), although in practice this is not always the case.

In what follows, the procurement process is outlined with points from each step to consider including in the initial RFQ.

1. Vehicle requirements: at a minimum, the initial specification should define requirements for
    a. Power consumption
    b. Momentum
    c. Power bus
    d. Allowable disturbance which is a factor of rotor balance
    e. Weight
    f. Volume
    g. Electrical interface
    h. Mechanical interface
    i. Radiation tolerance
2. Candidate selection
   Compare vehicle requirements to available RWA candidates. Consider using an existing design that closely matches requirements to control costs.
3. Compare vendor practices with program standards.
   Examine the vendor's configuration management and material review processes. These may be adequate, but it is still advisable for the buyer to have insight into the implementation of these practices throughout development so that the vendor's adherence to these policies may be verified. Vendor procedures should be compared with appropriate standards for factors such as environmental test [2] and soldered electrical connections [3].

   Using commercial-off-the-shelf components can be used to reduce cost, but may not always exactly match requirements. Parts from the NASA Parts Selection List (NPSL) should be used whenever possible; but parts obsolescence will make it likely that some parts will not be on the NPSL or will even be space qualified. These parts will require some degree of qualification testing. The thoroughness of this testing will have to be weighed against cost constraints. The requirements for Class S parts as listed in MIL-STD-883 [1] can be used as an upper bound for both reliability and cost.
4. Source selection
   The primary criterion for an RWA source selection should not necessarily be cost. The proposal that represents the best value, which is a carefully considered tradeoff between cost

and risk, should be chosen. Factors such as vendor track record, facilities, test capabilities and troubleshooting skill should be factored into any best value judgment. When problems occur, the vendor's expertise and resources will be the primary determinants in finding timely resolutions. Cost and schedule overruns could more than offset any initial price advantages presented by less capable vendors.

5. Program development & manufacturing
   It is important to establish a consistent and reliable stream of information from the vendor, starting early in development cycle and continuing on through delivery. This enables the project to get early insight into potential problems and decreases the possibility that such problems will go unreported. In addition to the standard gated review meetings, the customer should have a representative participate in weekly status meetings (can be teleconferences) and should be provided monthly program reviews. The customer should also have a representative on the parts, materials, and process control board. Nonconformance reporting should be provided at all levels (not just at the assembly level) and the customer should require access to test data and build books to ensure that any potential problems are brought to light. Finally, the vendor should be asked to take pictures throughout the manufacturing process for use in any anomaly investigations that might occur.
6. Sell-off
   Vendor should provide a final data package at sell off as described in Aerospace Report No. TOR-2008(8583)-3859: [2]

   The contractor shall establish and maintain data packages for all units including all subcontracted units. The packages shall contain the complete chronological history from the beginning of unit build through final acceptance of the component. The term unit, as used herein, means an assembly, subassembly, or combination of parts mounted together, normally capable of independent operation and performing a discrete function. Examples are: transmitter, power supply, or reaction control unit which are normally tested as separate units. A single part is not a unit. A fully integrated data package, which shall be available for Government review, is required for each serial number of the flight and qualification items, including spares, and shall include as a minimum the following:

   a. *Complete unit build history starting at the lowest level of assembly.*
   b. *Identification of manufacturing instructions and processes used to build the unit.*
   c. *Complete build inspection and test records, including physical and functional discrepancies, their resolution, and repair and rework history.*
   d. *Material Review Board (MRB) actions, waivers and deviations, where applicable.*
   e. *Test history including environmental test exposure and related measurements, where applicable, trend data across the testing, accumulative trend data across family of units, failures and anomalies during unit test, resolution, and retest.*
   f. *Identification of associated test equipment and test software, where applicable along with critical test calibration results.*
   g. *Associated failure reports including failure analyses leading to identification of root cause, disposition and corrective action.*
   h. *Identification of any unverified failure (a failure in which the root cause has not been clearly established) and analysis of worst-case repair if applicable. If in subsequent testing the failure never occurs again, rationale should be given for ascribing the failure to a cause other than flight hardware.*
   i. *Cumulative operating time or number of cycles and accumulative vibration and temperature exposures when applicable.*
   j. *Unit as-built configuration description including a configuration status accounting for the as-built versus as-designed configuration at the time of unit delivery.*

k. Records reflecting traceability of parts, materials, and subassemblies installed.
l. Storage history.
m. History of the unit from the time it is first integrated into a higher assembly, to include: initial installation date; removal date(s); reason for removal; discrepancy and failure history; and traceability references to all inspection, discrepancy, failure, rework, repair and retest paperwork.
n. Product photographs when specified.

4.2 General Comments

Some general comments regarding reaction wheel procurements are:

1. If possible, avoid changes in the extremes of the required operating temperatures and increases in launch load requirements relative to past missions. These two items drive bearing selection and qualification.
2. Long lead items (bearings, motors, other) should be identified and an appropriate procurement schedule adopted.
3. Electronic components for the full program should be procured and qualified all at once and early in the program if not cost prohibitive. For single spacecraft acquisitions, every effort should be made to use the same components as previous reaction wheel builds if they were qualified under acceptable standards.
4. Have a project representative participate in weekly teleconferences, as these forums provide early insight on trends and issues.
5. Space parts are a small fraction of the total of any business base and have requirements that make them unattractive from a profit point of view. Thus, extra effort is required to ensure that specifications and schedule will be met.

5. Surveillance Practices

This section contains recommendations and considerations for RWA surveillance. Section 5.1 provides recommendations for qualification and life testing. Section 5.2 provides recommendations for surveillance during the manufacturing process. Section 5.3 provides some considerations for delivered RWAs. Section 5.4 provides considerations for on-orbit RWAs.

5.1 Life Test and Qualification Test Results

Wheel designs should be validated through both life and qualification tests. Previous tests may be used, but must be applicable to the current mission. It is unusual to find a prior test with conditions and duration that match a new mission profile. The effects of deviating from actual mission conditions should be well understood.

1. Accelerated life tests are only valid for one particular failure scenario. For example, accelerating the number of zero-crossings and increasing the time spent at low-speed does not predict the time-to-failure for a process that is a function of the total number of cycles or one that is driven by prolonged, high-speed quiescent operation.
2. Higher test preload is not always more stressful on the bearing. Higher temperature is not always more stressful. Lower speed is not always more stressful.
3. Have a bearing expert review test requirements to determine if acceptance/qualification/life test program is adequate for the design/mission.

5.1.1 Physical Bearing Inspection after Qualification/Life Tests

Bearings should be carefully inspected after qualification/life test. Common results and recommendations for this inspection are presented.

1. Black grease after short-term testing is an indicator of distress and should result in further study.
2. Frosted tracks (dull finish) on races/balls are common and are usually benign.
    a. It is wise to perform a profilometry trace across the track if it is accompanied by moderate to severe lubricant discoloration. These bands are unacceptable if profilometry shows a measurable loss of material due to particle dents. Other bearings in the lot should be inspected to determine if a processing problem has occurred with the bearing manufacturer.
    b. If accompanied by discolored lubricant, frosted tracks should also be inspected with a scanning electron microscope. Benign dents due to hard particles will appear as many depressions with the same shape. However, if the frosting is found to be composed of deposits of metallic wear debris, this is an indicator of more pernicious wear and lubricant distress.
3. Glazed bands (with a mirror finish) on races/balls indicate surface distress due to harsh tribological conditions. These are usually accompanied by deposits of metallic wear debris as described above and “duning” in the ball path. Check for causes such as high conformity, high speed, and low temperature.
4. Short term wear (rut depth) after run-in should not exceed 5 μin. It is not unusual to see a loss of the original honing lines on the raceway after run-in; however anything beyond 5 μin is generally considered to be a sign of harsh tribological conditions. It is not necessarily a sign

of imminent failure, but one should watch closely for further degradation when this degree of wear is found.

5. Determine if the stationary rings (inner rings attached to stator which should not move) are rotating in the housing during use. This is done by inspection.
6. Inspect ring/housing interfaces for fretting. If it is found, consider whether it may result in restricted motion or misalignment in the future.
7. Check for Brinell dents (material deformation caused by contact stress) at the relieved dam and on the ball surfaces. The relieved dam is the lowered bearing raceway shoulder on the non-bearing contact side of angular ball bearings (Figure 5).
8. Fluorescent dye penetrant inspection should be performed if silicon nitride balls are used.

5.2 Manufacturing Process

Figure 6 shows a flowchart of the reaction wheel manufacturing process with recommended inspection points. The blue boxes are steps handled solely by the vendor, the green boxes are inspection points in which photographs and data are provided to the customer, and the red boxes are recommended customer inspection points at the vendor location. Each box contains a reference to the paragraph number that has associated recommendations. Throughout this entire process, photographs should be taken regularly, ideally anytime someone touches one of the components. These can be invaluable in tracking down anomalies.

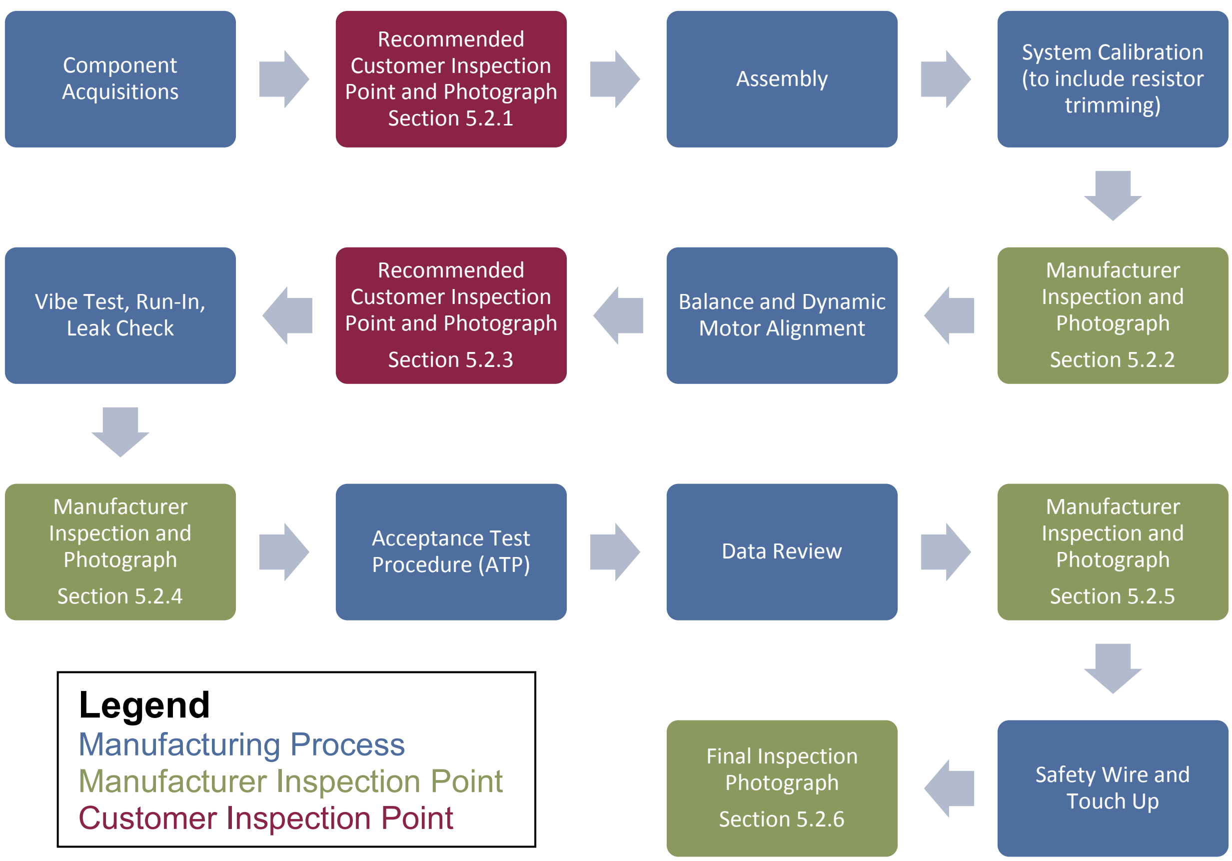

Figure 6. Reaction Wheel Assembly Flowchart.

The following describes aspects of the RWA manufacturing process that should be carefully monitored by the buyer at the inspection points.

5.2.1 Recommended Customer Inspection after Component Acquisitions

Prior to assembly, individual component procurements should be scrutinized. Recommendations for common problems with RWA components are presented in this section.

5.2.1.1 Bearing Acquisition

1. The buyer should perform a 100% visual inspection of races, balls, and retainer under 40X optical microscope before they are accepted into flight stock. During this inspection, he should look for:
    a. Divots in steel ball surface
    b. Brinell dents in the shape of a crescent
    c. Droplet shaped surface film
    d. Discoloration in raceway
    e. C-cracks on ceramic ball surfaces
2. The data from a low-speed dynamometer trace should be provided by manufacturer with each bearing. The buyer should perform an FFT of the data and analyze the peaks to look for signatures known as bearing defect frequencies. The manufacturer should be able to explain all findings.
3. Ask to see particle count numbers for each bearing, taken after a solvent flush is filtered. Many types of particles are allowed, even in large numbers. Hard particles (silicon carbide, diamond, etc.) however, require a decision by the buyer on whether to keep the bearing.
4. Critical bearing dimensions (bore, outer diameter, curvature, etc.) should be recorded, and should accompany each bearing. Ensure that these meet the tolerances on the bearing specification.
5. Ensure that the bearing curvature meets the specified requirement (51.6%), and that it will not exceed the limits mentioned above when the bearing is clamped in place.
6. Ask if the manufacturer has taken normal precautions to ensure acceptable ball size distribution and that no changes in processing have occurred that might have required replacement of a subset of balls.
7. Do not accept changes from previous cleaning practices without significant operational testing. Do not accept assertions that a modified process will lead to cleaner bearings. This is not always true and cleaner is not always better. Cleaning does not necessarily have a positive effect on surface chemistry.
    a. Confirm wettability of races and balls from lot sampling. Have a surface chemist review the manufacturer's wettability measurements.
    b. Pay close attention to any deviation from heritage processes.
    c. Beware of changes due to obsolescence of cleaning materials, particularly in light of ozone depleting chemical (ODC) solvent issues.

5.2.1.2 Retainer Manufacture/Acquisition

1. Cage designs should have RWA heritage for that particular bearing size or testing may be necessary.
2. Ensure that no silicone is left on the phenolic stock after manufacturing as it is often used in molds. Silicone contamination can be very dangerous because it can severely degrade lubrication performance. It is not unusual for phenolic manufacturers to forget that this is important to a small subset of their customers.

3. Look for premature retainer wear as a result of deburring. Deburring is the process of removing raised edges or small pieces of material (burrs) attached to a work piece, usually after machining.
4. Phenolic retainers must be thoroughly dried using a vacuum oven and then vacuum impregnated with oil for at least two weeks.

5.2.1.3 Lubricant Acquisition

1. Verify that the lubricant has been used before in RWAs and has extensive orbital experience. Otherwise, qualifying the lubricant will be necessary.
2. Perform chemical analysis of a lube sample on a lube-lot basis. The chemical composition may not be as claimed. Evidence of chemical analysis of the exact lot used in the bearings must be provided.

5.2.1.4 Electronics Acquisition

1. Perform a 100% visual inspection of all electronics boards. Look for discolorations in piece parts, burned or broken traces and poor solder jobs.
2. Verify that all components match the ones used in the original design. If obsolete components are replaced by new ones, qualification of the new parts should be verified.

5.2.1.5 Lubricant Quantity and Distribution

Use heritage lube quantities for a given bearing size or perform up-front testing of quantity effects if they are to be changed. Only enough lubricant to provide a micron-thick film between surfaces with some excess lube (to resupply the contact) is required. Typically, contractors use grease fills of ~20% of the internal void volume in the bearing. The void-volume ratio is the percentage of the volume of empty space within the bearing that is available for retaining or distributing a lubricant.

5.2.2 Post-Assembly and System Calibration Off-Site Inspection

This inspection will be performed by the manufacturer, but data should be provided to the customer. The assembly and calibration processes should be scrutinized. Nonconformance reports should be examined for inconsistencies in nonconformance handling. Request that photographs are taken during motor alignment and balancing.

5.2.3 Pre-Vibe Inspection

After initial assembly, electronics calibration, balancing and dynamic motor alignment, and prior to vibration testing, a quality assurance representative and appropriate experts should be sent to the vendor facility to physically inspect the assembly and to review the build book. Data from the first Manufacturer Inspection Point (Section 5.2.1) should be evaluated along with new data from balance and motor alignment. Also, request that photographs of the reaction wheel assembly and test set are taken during vibration testing and run-in. The following recommendations apply to the assembly process and should be verified at this inspection.

5.2.3.1 Bearing Installation

1. Forces applied during assembly must not be applied through bearing preload path, otherwise the preload mechanism may be damaged.

2. Clamping force should be applied from the mounting shoulder only to the base of ring, up to the radius of the bottom of the raceway (Figure 5).

5.2.3.2 Electronics Installation

Look for workmanship issues such as visibly damaged components, poor solder quality and broken or damaged traces.

5.2.3.3 Assembly Performance

Compare drag torque (motor current) with previous RWA builds.

5.2.4 Post-Vibe Test and Run-In Off-Site Inspection

This inspection will be performed by the manufacturer, but data should be provided to the customer. Request and review the Acceptance Test Plan to ensure that tests will verify requirements and request photographs be taken during acceptance testing. At a minimum, the following data should be provided and evaluated after acceptance testing:

1. Bearing preload yield – the number of units that do not meet the preload requirement. This should be measured during manufacture.
2. Bearing runout yield – the number of units that do not meet runout requirement. This also should be measured during manufacture.
3. Breakaway torque – the torque required to initiate bearing motion.
4. Drag torque – friction force opposing motion. This can be measured through motor current.

Look at trending across RWA builds for each of these parameters. They should be fairly consistent across builds. Trending up or down toward limits could indicate a manufacturing issue.

5.2.5 Data Review Off-Site Inspection

After acceptance testing, the data should be carefully reviewed to verify that RWA requirements have been met. Look at trending from previous functional tests and verify consistency. One key specification to look at is drag torque, which should be stable or decreasing. Verify that wheel test data is from flight system hardware. It is not unheard of to find data from previous builds in test data. Also, make sure that photos are provided at progressive levels of assembly for inspection purposes as well as for investigative purposes should a failure review be required.

5.2.6 Final Inspection

Another customer inspection is not required prior to delivery; however the complete data package should be closely inspected at this time. The entire build book should be reviewed and should be consistent with the manufacturer's procedures throughout. All of the recommendations from previous sections should be included, as this is the final opportunity to catch any issues prior to delivery.

5.3 After Delivery

The following should be considered after the wheels are delivered.

1. Chirps and squeals may be emitted by the wheel during acceptance testing or early after delivery. These sounds, early in life, are normal and are typically benign. They are caused by viscous coupling between the ball and cage due to excess lube. These are known as “wet cage instabilities” and should reduce with continued run-in.
2. Leaks in housings may occur at any time for no apparent reason. These are normally detected as extra drag, sometimes referred to as “windage drag,” during operational tests.
    a. Testing after extended storage may result in damage to lubricant if oxygen and water have infiltrated the housing. This can result in reduced lubricant life. Bearing removal and replacement is sometimes recommended if significant operation has occurred in a contaminated atmosphere.
    b. Rings made of 52100 steel will oxidize quickly in a humid environment.
3. Some RWA manufacturers recommend regular periods of exercise during storage.
    a. This is usually done to redistribute lubricant, which tends to creep and collect at capillaries between ball/race, ball/cage, and ring/housing. Oil does not usually flow in significant quantities due to gravitational forces, so the orientation during storage is not usually important.
    b. In some cases of prolonged storage (primarily in scarcely lubed applications like inertial gyroscopes), surface creep leaves dry spots in raceways.
4. It is not unusual for RWAs to be recalled after months/years of storage. If recalled, watch for damage to shaft/housing when bearings are retrofitted. This will appear as Brinell dents on the balls and races, and induced vibration at the ball roll frequency (rate at which balls revolve about their own centerline) and/or the ball pass frequency (rate at which balls pass a particular location on raceway).

5.4 On-orbit

The primary indicator of reaction wheel health on-orbit is motor current. An increase in the current required to maintain a given speed indicates increased bearing friction, and any abrupt changes to motor current or an upward trend that increases more rapidly than previous builds can be an indicator of bearing distress. Some RWAs have other sensors that can provide limited information such as temperature sensors, but motor current is the most significant metric to track.

Some attitude control methods only use three RWAs and leave a fourth redundant RWA idle until needed. In these cases the inactive wheel should be exercised regularly in order to maintain lubricant distribution. Manufacturers should provide guidelines on how to exercise inactive wheels on-orbit.

6. Anomaly Investigation

An anomaly investigation was performed for satellites with RWAs launched from 1980 to 2010. The anomalies were drawn from the Aerospace Space Systems Engineering Database [4] and over 200 anomalies were identified. Approximately 60 were deemed to have enough information to determine a probable root cause. Five anomaly types were identified: electronics, motor, structural, bearings/lubricant, and flight software. Figure 7 shows a breakdown of the number of anomalies by mission phase and anomaly type. Figure 8 shows the breakdown of catastrophic in-flight anomalies by type. Each anomaly type is described in this section.

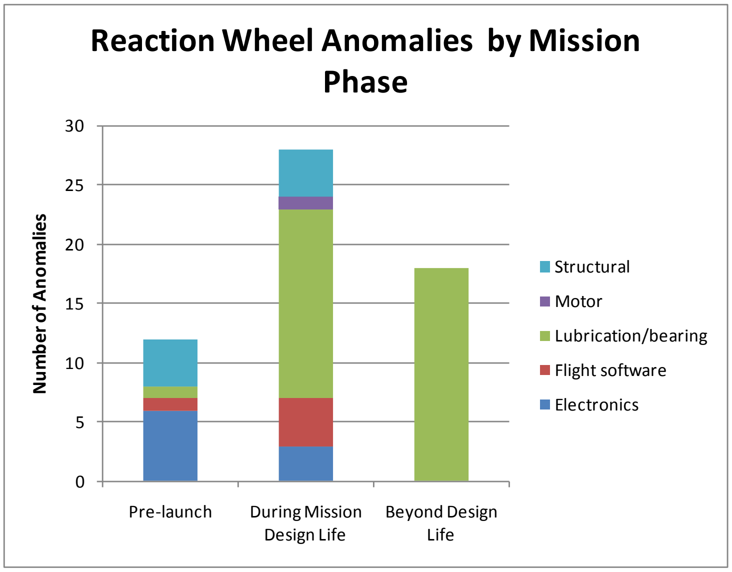

Figure 7. Reaction Wheel Anomalies by Mission Phase.

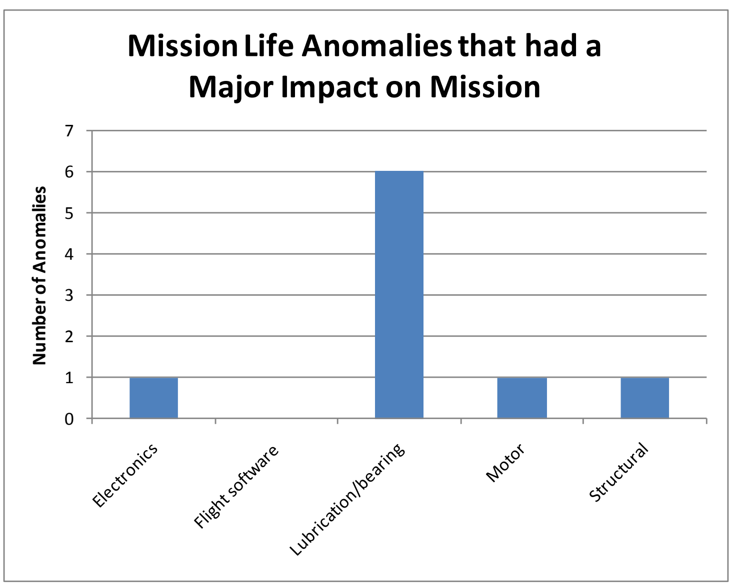

Figure 8. Major Reaction Wheel Anomalies.

6.1 Electronics

Electronic anomalies can occur on both power and control electronics and can be divided into two categories: workmanship and design. Typical workmanship issues include wire disconnect, improper soldering, fuse board wiring errors, and failed resistors, while design issues include improper part selection or wiring board design. The buyer should perform a visual inspection of all electronics components to catch these problems early. He should look for discolorations in electronics, burned or broken traces and poor solder jobs. Verify that all components that are used match original design. If obsolete components are replaced by new designs, qualification of new parts should be verified. Operational and acceptance testing should catch many of the issues not caught by inspection. Figure 7 shows that the majority of electronic anomalies occur during pre-flight testing.

6.1.1 Specific Incident

One example of an RWA electronics failure occurred on-orbit. The failure was attributed to a leaky polycarbonate capacitor in the wheel speed integrator with damage from radiation exposure hypothesized as the root cause. A method was developed to clear this condition. There was no sign of overstress to the assembly as a result of this condition. To reduce the chance of electronic anomalies due to component failure, it is important to ensure that radiation requirements are set to appropriate levels and that requirements are met. To ensure that electronics will work properly throughout the duration of the mission, subject matter experts (SMEs) need to be consulted to determine the level of radiation hardness required for the mission, and RWA electronics should be built to that specification. Appropriate radiation SME consultation should not be passed up in order to save costs.

6.2 Motor

Motor anomalies are specific to the motor itself and, as shown in Figure 7 and Figure 8, are very infrequent in all phases of mission life. Moreover, it is not always easy to decouple a motor failure from a failure with the electronics that drive the motor. Motor coil redundancy can help to mitigate the risk of a motor anomaly.

6.3 Structural

Structural anomalies occur as a result of faults in the housing and support structure of the RWA. These types of anomalies are uncommon, but can occur in both pre-flight testing and during mission operations. Structural anomalies can be divided into two categories: workmanship and design. The former should be detectable pre-flight through acceptance tests; the latter, on the other hand, might not be detectable until an on-orbit anomaly occurs. Examples of workmanship issues include loose screws and housing cover leaks due to improper soldering. An example of a design issue is improper material selection. Using an existing design can help to mitigate this risk.

6.3.1 Specific Incident

An example of an in-flight RWA structural anomaly was attributed to growth during vacuum conditions of small bubbles in the tape used to line the inner housing of the assembly. The bubbles likely expanded over time due to inevitable creep in the amorphous acrylic adhesive. This particular RWA was designed to maintain a very close tolerance gap between the rotor and the housing, and the housing was lined with tape so that loads induced by launch vibrations would be absorbed by the tape rather than the rotor bearings. Attempts to restart the wheel failed. The manufacturer later redesigned the RWA to no longer use the small radial gap for snubbing. The gap has been increased, and the radial snubbing is performed on a small diameter on the shaft, with no need for tape on the snubbing surface. This anomaly demonstrates how an RWA structural anomaly due to a poor design choice may only be detected after launch, though this may have been caught pre-launch with thorough vacuum testing. Designs with proven flight history should be used to reduce the risk of this type of anomaly.

6.4 Flight Software

Flight software issues deal with anomalies in the main satellite computer. Issues include improper software patches or lack of sufficient patches and are often caused by operator error. Flight software anomalies are infrequent and tend to occur during the mission design life. They are often easily mitigated through updates to the flight software and rarely have a major impact on the mission itself. As shown in Figure 8 none of the flight software anomalies analyzed in this study had a major impact on the mission.

6.4.1 Specific Incident

An example of an in-flight RWA software anomaly occurred when one of the RWAs on a mission passed its red line limit speed. The anomaly was attributed to a new ACS algorithm implemented earlier in the day. The new ACS pitch pointing algorithm actuated the wheel much more than in the past. Consequently, new limits were required for wheel speed, motor current, and digital sun sensor errors. To mitigate flight software anomaly risk, software updates should be thoroughly simulated prior to any software patches.

6.5 Bearings/Lubricants

Bearing/lubricant anomalies deal with issues in the bearing housing. It is hard to decouple bearing problems from lubrication problems, since issues with lubricants almost always cause problems with the bearing. Also, degraded lubricant may be a symptom, not a cause, of problems elsewhere in the mechanism. Areas of concern include lubricant degradation, evaporation, debris, and bearing lock.

Bearing and lubricants cause the most of the in-flight anomalies. In our study they caused twice as many major mission anomalies as all the other types combined. Some examples of lubricant issues that have been observed over the years on various space programs are:

- Incorrect base oil, additives, or application
- Depletion caused by mechanical forces, surface tension, evaporation, chemical degradation, and improper storage
- Deterioration
- Contamination
- Excess lube (torque instabilities, retainer instabilities)
- Kinematic starvation (exceeding speed/temperature limitations)
- Oiler failure

Some example bearing issues that have been observed over the years include:

- Contamination (hard particles from grind/hone operations)
- Improper preload
- Improper balancing
- Poor design (exceeding speed or temperature limitations)
- Poor material choice
- Improper assembly (excessive clamping force, misalignment, ring distortions)
- Manufacturing/metallurgical defects
- Exceeding static capacity (launch vibe)
- Retainer imbalance, retainer instability, retainer fracture
- Ball size variations

6.5.1 Specific Incidents

6.5.1.1 Vibration and Contamination

During acceptance testing of an RWA, noisy bearings were noted after vibration testing. Disassembly revealed bearings with fretting damage. Debris, presumably from the fretting, was present and the lubricant was in a degraded state. The wear debris was the most probable cause of the bearing noise. Analysis of the lubricant revealed the most likely cause of the damage to be a silicone compound contaminant that was traced to a batch made by the lubricant supplier. Cross contamination with utensils from production of the silicone fluid for other applications had occurred. The incident was limited to one batch and unrelated quality control changes have prevented relapse; however over 130 wheels were affected by the one batch.

A series of tests on the performance of the contaminated lubricant were conducted. In general, it performed adequately, but severe de-wetting was observed. On the basis of that result, all contaminated bearings were replaced, many by cleaning the bearings and re-lubing per approved procedures. Performing chemical analysis of lubrication on a lube-lot basis will ensure that the appropriate lubrication is used and that the lubrication has not been contaminated.

6.5.1.2 Lubricant Loss

Finally, one RWA failure was uncovered that was attributed to stiction caused by lubricant loss due to extended ground storage. Make sure to follow vendor instructions for wheel storage closely to mitigate risk of losing lubricant during storage.

7. Concluding Remarks

This study has examined best practices derived from many RWA procurements carried out over decades of development. A few key themes arise from this work. The first and foremost is that bearings and lubrication are perhaps the most critical technology involved in an RWA procurement. For any acquisition, a judicious use of project resources would be to employ a bearing expert at critical points in the procurement cycle. It is also crucial that programs follow appropriate procedures to acquire bearings and lubrication and that the procedures be closely monitored. In this report, we have cited many guidelines and provided references to military standards that have been successfully used to buy RWAs. The use of these best practices and processes will greatly decrease the risks of a catastrophic RWA failure.

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Dr. Andrei L. Doran	Control Analysis Department
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Dr. David J. Carré	Micro/Nano Technology Department
Jennifer N. Tanzillo	Electromechanical Control Department
Luke A. Rinard	Electromechanical Control Department
Marc R. Hayhurst	Engineering Data Analysis and Integration Department
Dr. Michael R. Hilton	Mechanical Systems Department
Dr. Peter P. Frantz	Micro/Nano Technology Department
Dr. Robert J. Kinsey	Planetary and Robotic Missions Directorate
Stephen C. Ringler	Program Development
Dr. Walter H. Chung	Electromechanical Control Department