

Mars Pathfinder Lander Deployment Mechanisms

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Abstract

The Mars Pathfinder Lander employs numerous mechanisms, as well as autonomous mechanical functions, during its Entry, Descent and Landing (EDL) Sequence. This is the first US lander of its kind, since it is unguided and airbag-protected for hard landing using airbags, instead of retro rockets, to soft land. The arrival condition, location, and orientation of the Lander will only be known by the computer on the Lander. The Lander will then autonomously perform the appropriate sequence to retract the airbags, right itself, and open, such that the Lander is nearly level with no airbag material covering the solar cells. This function uses two different types of mechanisms — the Airbag Retraction Actuators and the Lander Petal Actuators — which are designed for the high torque, low temperature, dirty environment and for limited life application. The development of these actuators involved investigating low temperature lubrication, Electrical Discharge Machining (EDM) to cut gears, and gear design for limited life use.

Summary

The complex EDL sequence begins with a cruise stage separation at 8500 km altitude and 6100 m/s (13,645 mph or Mach 18 at 1 atm). After the deployment of a parachute and the descent of the Lander on a 20-m long bridle, the airbags inflate seconds before RAD firing and bridle separation. The Lander strikes the surface at roughly 22 m/s (50 mph), 35 minutes after cruise stage separation. After bouncing as high as a nine-story building and continuing to bounce for one to fifteen minutes, the Lander should come to rest somewhere in the Ares Vallis in southern Chryse Planitia on Mars on July 4, 1997. The airbags will be covering the outside surfaces of the Lander and may be either intact and partially inflated or ripped and deflated.

Upon coming to rest, the Lander must autonomously determine its attitude and condition and perform the actions required of the Airbag Retraction Actuators (ARA) and Lander Petal Actuators (LPA) to flip the Lander over, if needed, and open upright on the planet surface. The Mars Pathfinder Lander Retraction and Deployment Sequence was developed to solve some challenging and diverse technical requirements. The Lander is a tetrahedron, roughly one meter in diameter. It consists of a triangular base petal with three similar triangular side petals (Figure 1). Each of the four petals is protected during impact with Mars by a large 6-lobed airbag made of Vectran fabric (similar to Kevlar). The final resting state of the Lander is random, but it will most likely come to rest on the rocky surface with one of the four petals down. At this point, the airbags are slightly limp and draping over the petals.

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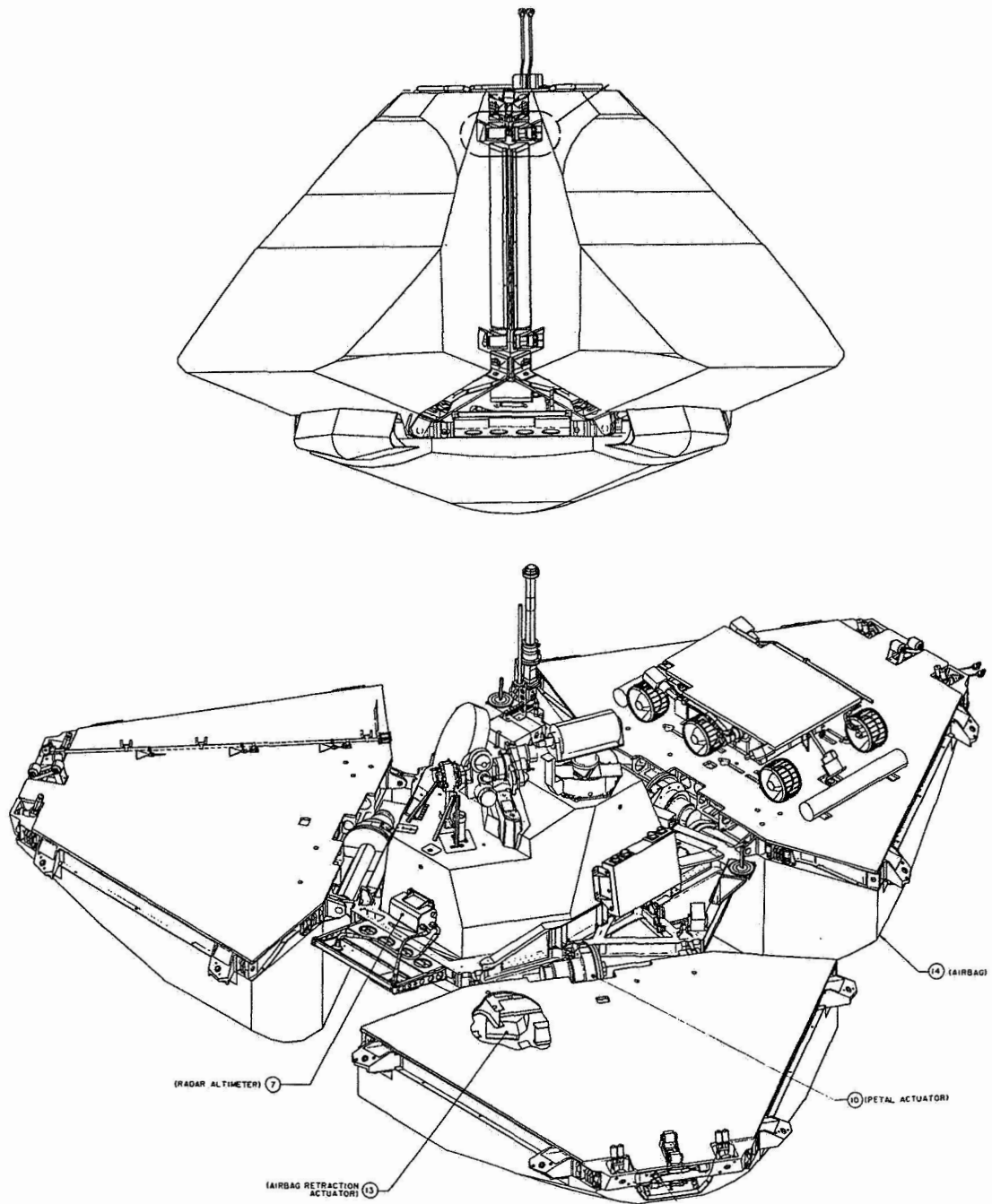


Figure 1 Mars Pathfinder Lander Stowed and Deployed

Sequence

Since the antenna used to communicate with Earth is located inside the closed Lander, the sequence must be completely autonomous and able to respond to the unknown landing configuration. Not only must it not give up or get into a dead end or infinite loop, but it must also be simple enough to be tested. This was accomplished by first determining the orientation (out of three basic configurations) of the Lander: base-down, side-down (any one of three), or nose-down. Figure 2 shows the flow chart of the Sequence. Each of these conditions requires a specific sequence to retract and deploy optimally. However, if the accelerometers or motor encoder telemetry should ever fail, the sequence must still enable the Lander to get upright and open. This is done by retracting all bags and deploying all petals. This results favorably, but the bag material sometimes covers parts of the solar cells. Nominally, for a side-down condition, the Airbag Retraction Actuators retract the three of the four bags on which the Lander is not resting. In doing so, the retraction cables, inside the bags, act like drawstrings to open vent patches and cinch the bags simultaneously. Five retraction cables, each about 5.7 m (224 inches) long, are retracted onto a spool inside the ARA. After the bags are retracted, the Lander again senses the gravity vector and begins to open the bottom petal first by turning on the appropriate Lander Petal Actuator; the other two petals follow. This is done to minimize the moment of the flipped mass and to protect the science payload. The final state is having all four petals coplanar, thus allowing the camera to take pictures, the communication link with Earth to be established, and the Rover to drive off the petal. Lander leveling is possible, if required.

The least likely orientation is having the Lander balanced on the top of the tetrahedron. This orientation is remarkably stable on level ground and creates a great challenge to move the center of mass over the pivot point. This is actually achieved with the use of the airbags. The airbag on the petal toward which the Lander is leaning remains unretracted, while the other bags are retracted to bring them closer to the Lander c.g. The two petals opposite the unretracted bag are opened only by 20°, so they are orthogonal to the base petal, hence the tallest they can be. The final bag is then retracted. The drag force of the bag is usually sufficient to pull the Lander onto its side, thus initiating the sequence to re-start using the side-down option.

Testing of the Sequence was performed on a full-scale, Mars-simulated terrain at ambient temperatures and also in a vacuum chamber at Mars temperature and pressure (-100°C and 8 Torr) without rocks or terrain. It was found that, even at Earth-weight, the Sequence was successful every time under normal and nominal worst-case conditions; only manually created “impossible situations” would result in failure.

JPL Mars Pathfinder
CONTROL FLOW FOR AIRBAG RETRACTION
& PETAL DEPLOYMENT V2.2.2

Designed by G. R. Gillis-Smith 8/4/95
Re-Entered by R. Manning 11/9/95
Version 2.2 updated by G. Gillis-Smith, Brad Swenson & RM12/29/95
Version 2.2.1 clarification RMM & GG-S 1/15/96
Version 2.2.2 clarification RMM & GG-S 1/16/96

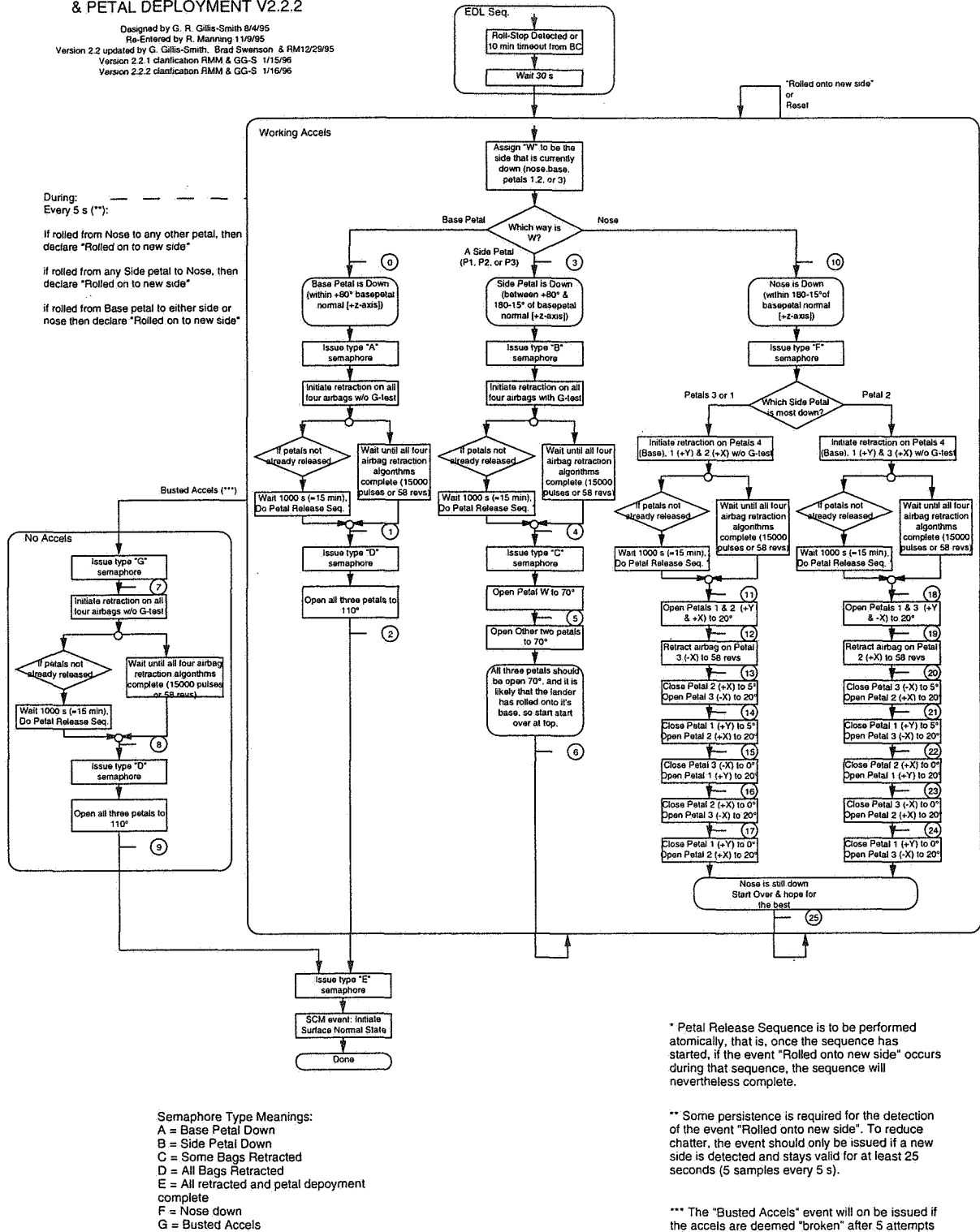


Figure 2 Airbag Retraction and Petal Deployment Sequence Flow Chart

Airbag Retraction Actuator

The Airbag Retraction Actuator is a robust winching mechanism used to retract the four large airbags on the Mars Pathfinder Lander and requires a maximum pulling force of about 1550 N (350 lb), with a 2:1 torque margin, to retract the bags completely. The primary design criterion for the actuator was a high-torque, compact, and lightweight design. It employs two DC brush Maxon motors to drive 1550:1 five-stage planetary gearboxes, which both drive a single cluster spur gear, which drives a secondary spur gear and spool assembly, thus resulting in an end-to-end 8277:1 gear ratio (Figure 3).

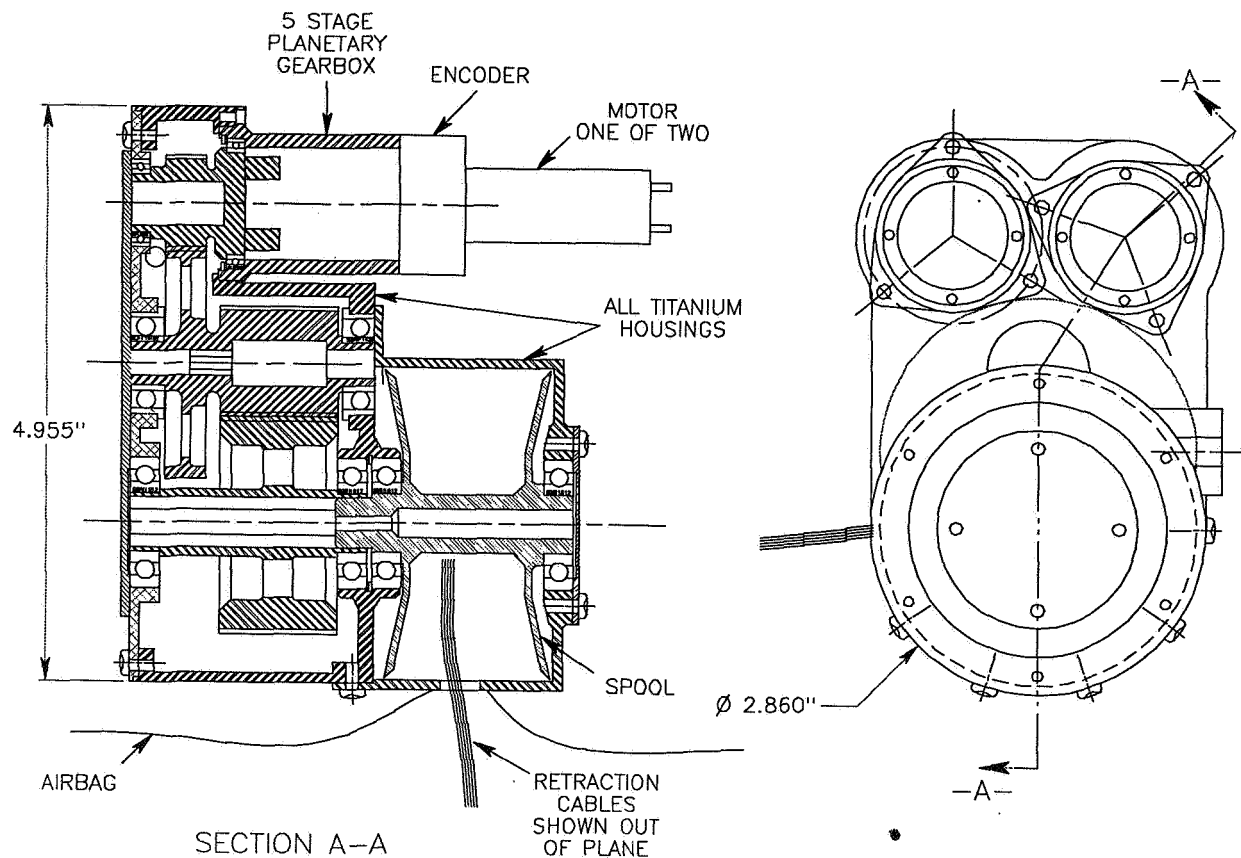


Figure 3 Airbag Retraction Actuator

Each motor has a stall torque near 15.8 mN-m (2.24 in-oz). Located between the planetary gearbox and one of the two motors in each actuator, an optical encoder records motor revolutions and hence the length of cable retracted. The five-stage planetary gearbox was designed, such that the ring gear and output can be customized and used in any other actuator (Figure 4). This gearbox was used in the gimbal of the Imager for Mars Pathfinder and will be used in a robotic arm of a 1998 Mars lander mission. For the ARA, the fifth-stage planet carrier is a bearing-supported pinion gear that drives the cluster gear. The final output stall torque of each motor/gearbox is about 11.3 N-m (100 in-lb). The total output stall torque of the ARA is about 96 N-m (850 in-lb) at temperature (Figure 6).

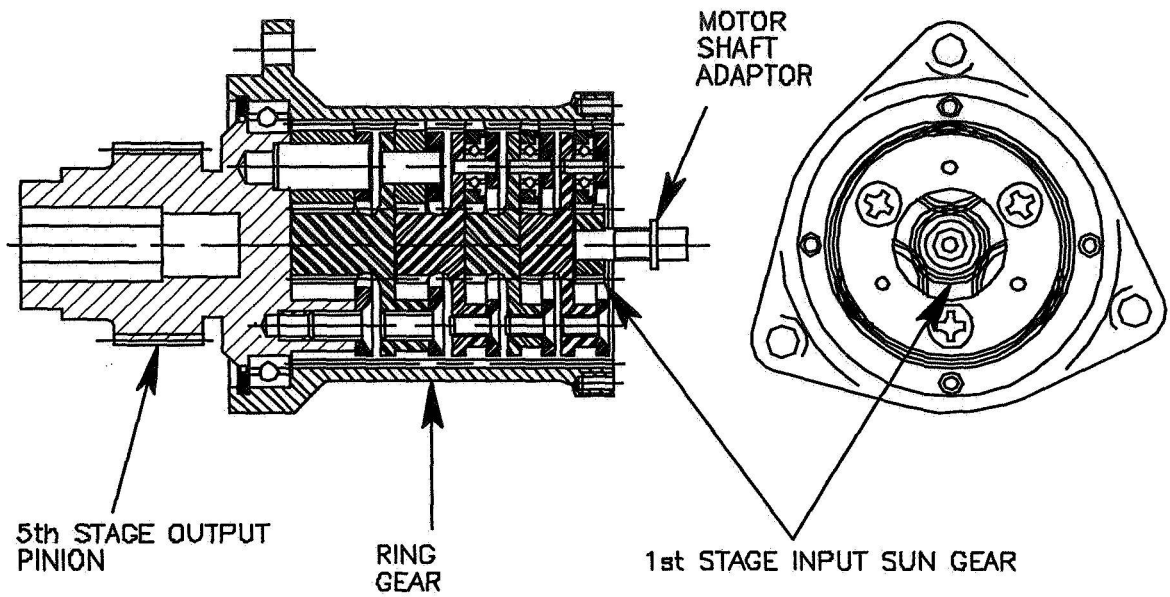


Figure 4 ARA Five-Stage Planetary Gearbox

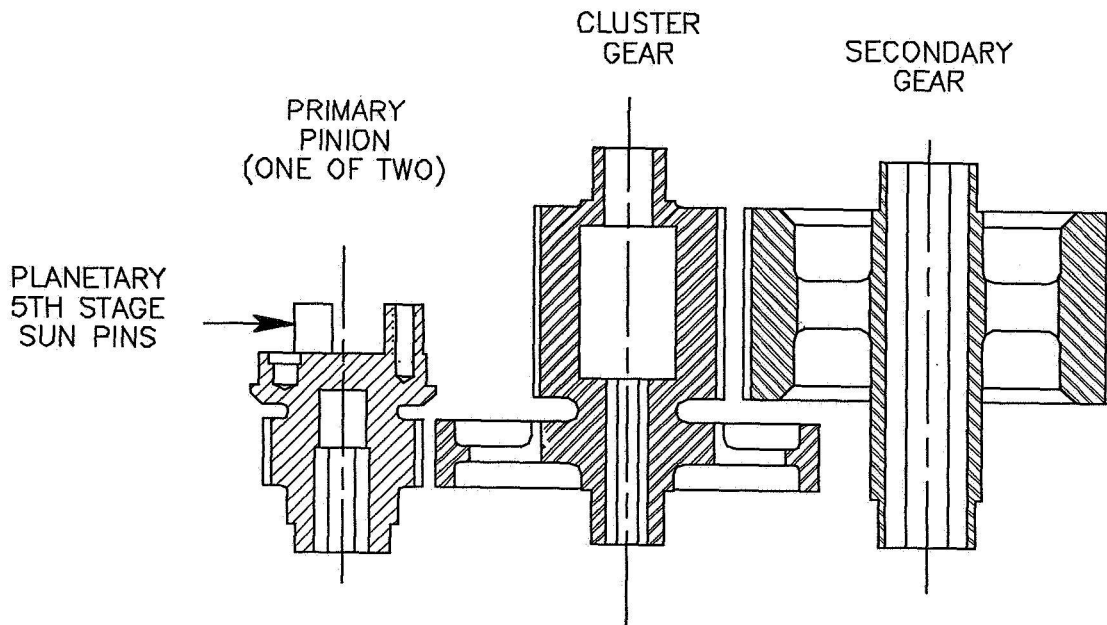


Figure 5 ARA Gears

ARA Speed/Torque/Current Qual Ambient Test

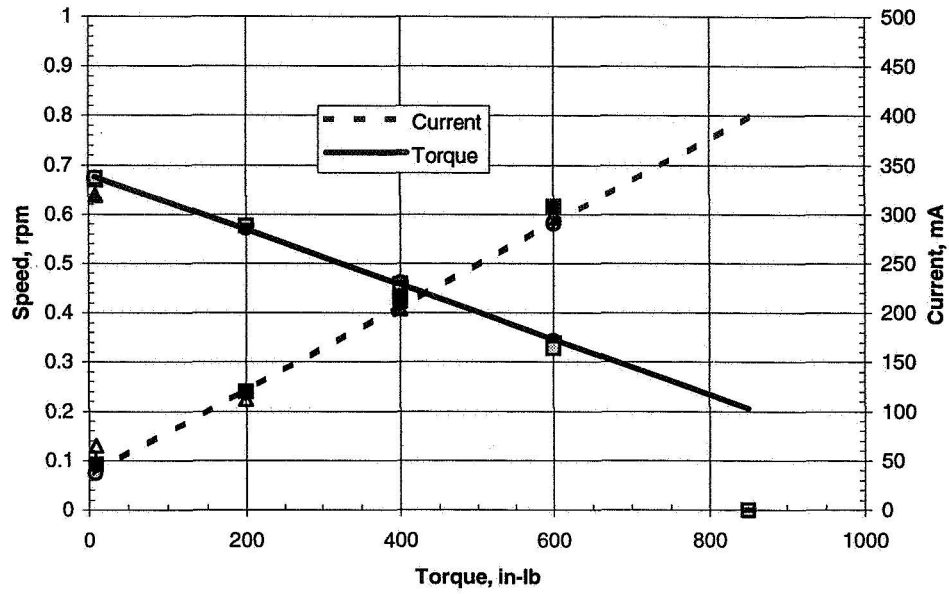


Figure 6 ARA Speed/Torque Curve

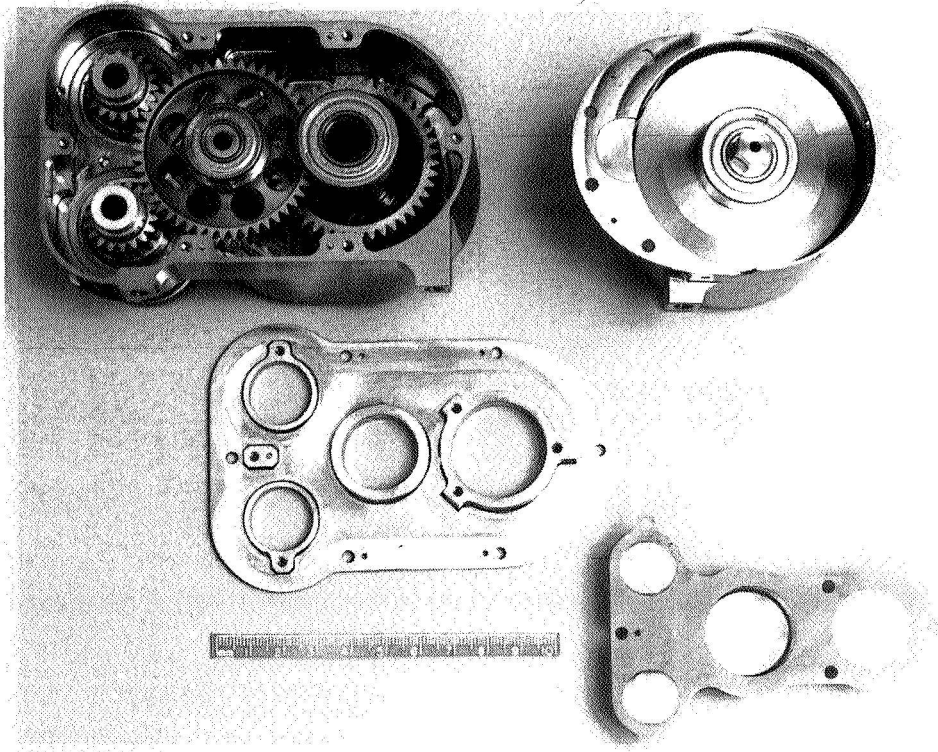


Figure 7 ARA Assembly



Figure 8 Airbag Retraction Actuator Exploded View

Nedox Plating on Gears and Bray 604 Grease Breakdown

The 5-stage planetary gearbox was designed and built by American Technology Consortium, who made the first two prototypes with Nedox-plated ring gear and planets. Nedox is an electroless nickel/Teflon matrix, known for its great wear properties. Since Bray grease 604, which contains Bray oil 814, has superior low temperature performance and was being used at low temperature in Mars Pathfinder Rover Actuators, it was used in the two prototype gearboxes. When testing the first prototype, the performance degraded and became more erratic. It was later determined that the hard Nedox coating had suffered sub-surface delamination on the last two stages and that the Bray had turned into a hard, tar-like substance (Figure 9). Studying the cause of Bray breakdown included researching both the Lewis Acids phenomenon and the impact of nickel particles in the gearbox. "Braycote 604 may be adversely affected by Lewis Acids, such as aluminum chloride, at elevated temperatures. Rubbing surfaces of aluminum, magnesium, or titanium alloy may react with Braycote 604 causing thermal degradation to the lubricant [2]." Lewis Acids act as catalysts to cause a breakdown of the oil in Bray grease, even at low contact pressures. It was found that the 814 oil in the Bray grease was not robust enough for the high contact loads at the asperity level and that the Nedox particles probably added to the high local loading. High contact loads cause rapid oil breakdown, thus producing identical results to a breakdown catalyzed by Lewis Acids. Visually, one cannot differentiate between mechanical grease breakdown and one catalyzed by Lewis Acids at lower loads. By eliminating the Nedox plating and choosing Bray 602, the gearbox experienced no degradation after repeated heavy testing at temperature. Bray 602 was selected because it is basically Bray 600, which contains Bray oil 815Z, with molydisulfide added for extra load-carrying ability and lubricity. It has similar low temperature torque properties as Bray 601.

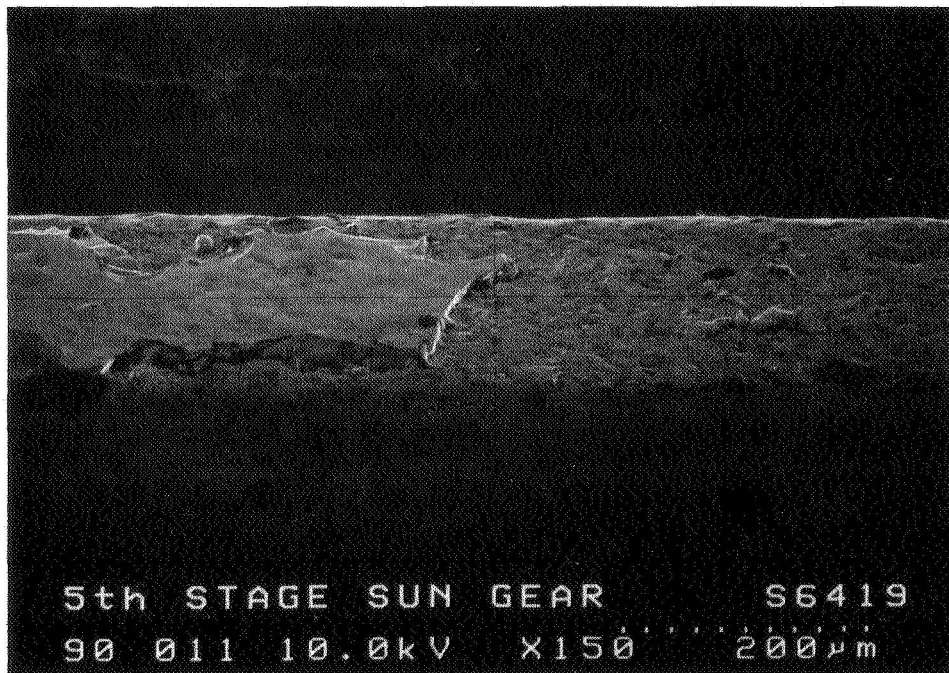


Figure 9 Nedox Failure on Tip of Gear Tooth

**Input Torque Test
Using 10% Bray 602 Greaseplate
3-Stage 81:1 Planetary Gearbox**

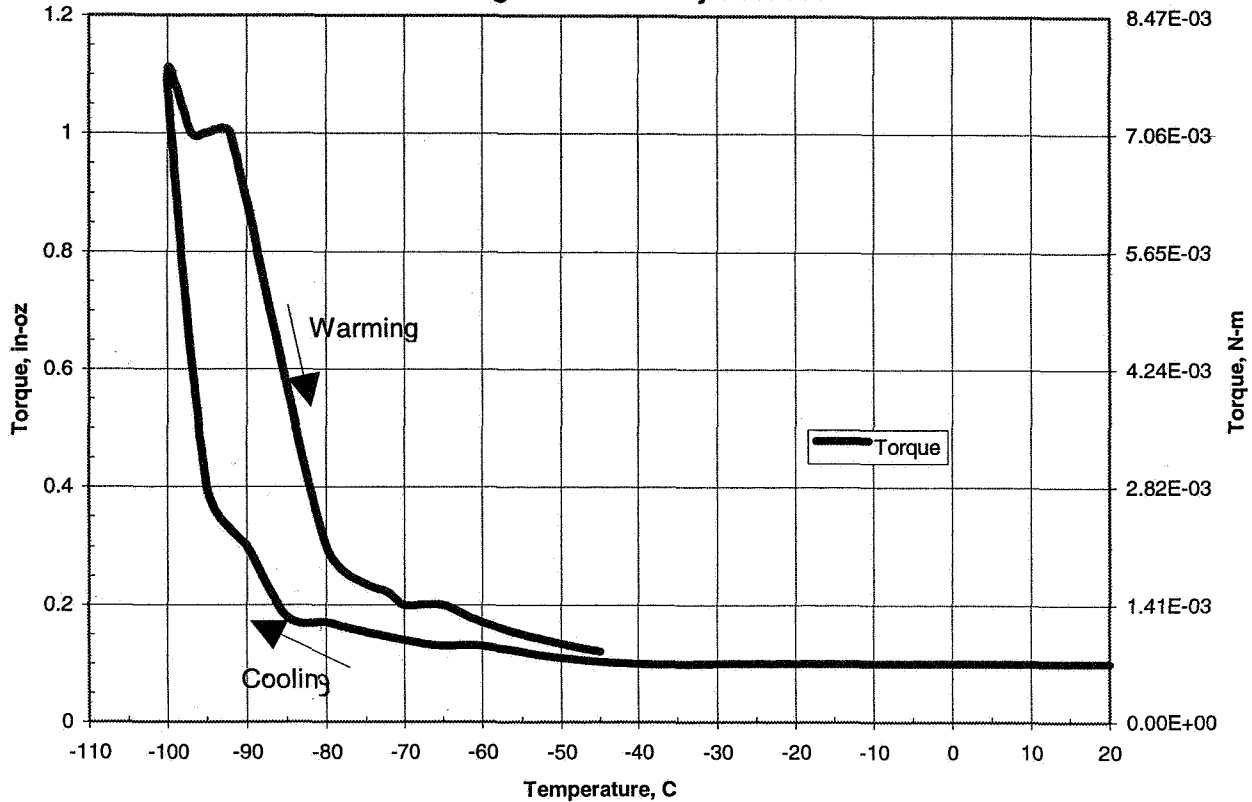


Figure 10 Grease Viscosity

Low temperature testing of Bray 602 grease

In order to determine the effects of low temperature on Bray 602, a quick test was done on three of the five stages of the ARA primary gearbox. The gearbox was cleaned and then grease-plated, using a 10% grease, 90% Freon TF solution, and mounted in a cold box with the primary stage open to the top. The primary sun gear was pressed onto a long insulating shaft, driven by a torque watch. The temperature was slowly dropped, and the torque required to turn the input sun gear was recorded (Figure 10). The hysteresis in the torque plot is believed to be due to temperature lag in the grease at the center of the gearbox. It could safely be assumed that the knee in the curve for this grease is about -75°C to -80°C, with almost no change in drag effects from ambient to -75°C but with 10-fold increases from -75°C to -95°C. This test determined that the lowest acceptable, flight-allowable temperature limit is -75°C, thus requiring heaters to maintain a safe temperature of -55°C.

EDM used to fabricate gears out of maraging steel

Using a new technology that makes the ARA interesting, the gears were produced by the wire and sinker Electrical Discharge Machining (EDM) process. This allows for infinite adjustment of gear tooth form and shape without the need for custom hobs, shapers, or new master gears for each new tooth form. This technology was first explored because the loading application was quite high and would require a tough material. The selected material, Maraging Vascomax C300, is usually heat-treated after final machining to obtain a yield strength greater than 2000 MPa (290 ksi), as well as good toughness properties. The challenges include both material shrinkage during heat treatment, thus deforming the gear, and required material strength beyond the capabilities of normal hob and shaper processes. With EDM, the material can be heat-treated prior to cutting the gear forms and final machining, thus allowing the part to have a perfect, as-cut gear tooth. Concerns of a re-cast layer that would weaken the tooth contact surfaces have been investigated. McLaren Formula 1 racing team uses EDM to manufacture their transmission gears in order to customize each gearbox for each race. However, they only use a set of gears once and then dispose of them.

In using EDM to machine the spur gears, it is important to have very accurate tooling to produce a gear with excellent form and surface properties. The ARA gears were designed to have an optimized tooth form for high load carrying capability for a limited life at peak loads. If the output gear were designed for infinite life, the face width would have been more than 10 cm for a 2.54-cm pitch diameter. These diameters were reduced to a 23.29-mm (0.917-in) PD and a face width of only 2.54 cm (1 in), but the tooth form was modified and had a 25° pressure angle. Instead of fabricating custom hobs, shapers, and master gears, EDM was selected to make these custom gears. A company was selected for their experience in high-precision EDM, but they had never before made gears. Using software written to produce gear forms, the gear data was entered, and a test gear was wire cut. This test gear was sent to a facility to analyze tooth form, surface condition, and tooth thickness. They found that the held tolerances were those of an AGMA class 10 gear, but one tooth was thicker than the rest. After researching both the EDM gear form software and the tooling used, it was discovered that the tool was not symmetric. After correcting the tooling, the flight gears were made. A second challenge was then apparent: only two of the four gears could be made using wire EDM; the other two had to be done with a sinker electrode. The electrodes were cut on the wire EDM machine, thus allowing for wire thickness offset. Premium grade, fine-grain graphite electrodes, one roughing followed by two finish, were used to produce gears of exceptional form and surface, with tolerances of an AGMA class 10 gear.

The re-cast layer is the outermost surface, which has been re-melted and weakened by the heat of the cutting process. The concern about the re-cast layer was addressed, and it was found that the type of power supply and the way the part is cut “reduced the recast to an almost inconsequential degree [1].” Additionally, electrolysis has been found to be a contributing factor in weakening parts made by EDM. The type of power supply used to cut the ARA gears is called an AE (Anti-Electrolysis) supply, a proprietary system of Mitsubishi. A DC power supply used in EDM has good machining speed, but electrolysis is high and produces more heat in the workpiece, thus causing more thermal damage. Using an AC power supply can improve the surface finish and

integrity, but the speed is half that of the DC system. In each AC cycle, one pulse chemically removes ions from the workpiece, and the pulse of opposite polarity removes less material but does not remove ions by electrolysis. "Even though (the) surface finishes are improved, we still have an electrolytically damaged workpiece, however lessened. This can be in the form of cobalt depletion, rust, oxidation, hydrogen embrittlement, etc. [1]" An AE generator capitalizes on the benefits of DC and AC systems but eliminates the disadvantages. The AC signal is rectified, such that all of the negative pulses are made positive. This creates a machining process that is fast and produces parts which are stronger and have improved surface finishes. In the case of the ARA gears, the microfinish was measured to be better than 24 rms. The inspection data for a 48-tooth gear, cut with wire EDM, and an 18-tooth gear, made with a sinker electrode, shows the variance from perfect tooth form. The average variance is 0.007 mm (0.00028 in) for the wire-cut and 0.013 mm (0.0005 in) for the sinker. It was also found that there was about 0.007 mm (0.00027 in) of taper on the sinker-made gears. These tolerances are roughly equivalent to an AGMA class 10 gear.

One other benefit of using EDM to machine the gears was that they were wire cut with an internal hex bore, since the cores of the gears needed to be lightened (Figure 7). This facilitated dyno testing, since a hex shaft adapter could be placed into any of the gears during actuation to speed/torque test the actuator at any of its stages.

Lander Petal Actuator

The Lander Petal Actuator (LPA) is a large, 5.7-kg (12.5-lb), high-torque, mission-critical mechanism used to flip over and open the 330-kg lander. The LPA primary design criterion was ultra high torque (12,000 in-lb) in a small package with minimal mass (Figures 11, 14). Output speed was a secondary requirement, since the time for both retraction and deployment needed to be less than two hours. Electronic-commutated, brushless DC motors (Figure 12) were selected because of their high torque and even higher reliability; in addition, one was already being developed for another project. The motor has a 0.14-N-m (20-in-oz) output stall torque, which drives a three-stage 49.3:1 spur gearhead, driving a 4:1 internal spur gearset inside the LPA. This outputs through a detent clutch to a 160:1 S-tooth harmonic drive, limited by a maximum (ratchet) torque of 1580 N-m (14,000 in-lb). Torque is transmitted to one hinge per petal by a titanium tube with square drive holes in each end. The output speed of this 31552:1 actuator is about 40 min/rev. The LPA operating temperature is -40°C to +35°C and was tested to -55°C and +55°C, with little change in speed/torque characteristics (Figure 13). This correlated with results of the ARA primary gearbox test, which found that the Bray 602 viscous drag characteristics behave linearly down to -75°C. Kapton film heaters were incorporated into the LPA flight design to maintain actuator temperature above -40°C.

Detent Clutch

The clutch is driven continuously between the input to the wave generator and the housing when the actuator is powered. The purpose was to create enough backdrive torque to support the weight of the lander when the actuator is turned off. It uses four opposing pairs of small compression springs, pressing on rollers that ride on the internal surface of a toothed ring gear. The advantage of this clutch is its torque limiting

performance, which is fairly independent of vacuum and temperature conditions. The running torque is slightly lower than the breakaway torque of about 1.36 N-m (12 in-lb).

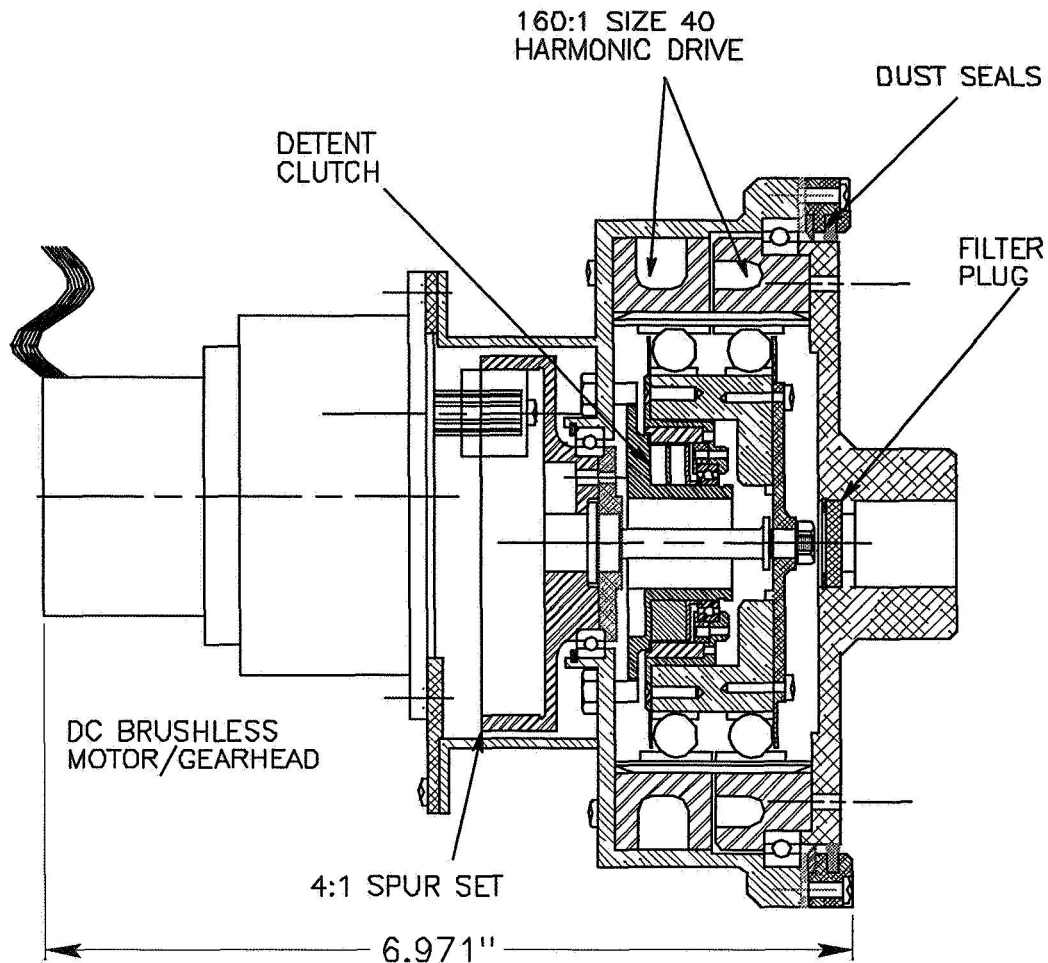


Figure 11 Lander Petal Actuator

Dust Protection

Several protective measures had to be implemented to keep the abrasive Martian dirt out of the actuator. The dust seals use both an outer felt seal and an inner Vespel wiper. The actuator must vent upon launch and refill upon landing, so a porous metal plug was incorporated into the drive hub to allow air passage without dirt (Figure 11).

Harmonic Drive

The S-tooth form harmonic drive is able to transmit more torque than the standard tooth form because of greater tooth contact area (Table 1). The new S-tooth enabled the use of the lighter and smaller size 40. Through dyno testing, it was found that the size 40 Harmonic would generally ratchet the flex spline gears before the motor would stall. This is undesirable but was deemed acceptable because the torque output would be limited to the value necessary to lift the Lander. These actuators were dyno tested by attaching the actuator to a 0.61-m (24-in) diameter pulley, 4 m high on a static test tower, that lifts stacks of steel weights. Cold operation was achieved by first filling a

purged Styrofoam box with liquid nitrogen and cold nitrogen gas and then re-warming with a gas heater.

The circular splines exhibited acceptable performance after lightening from 1.02 kg (2.25 lb) to roughly .68 kg (1.5 lb), much to the amazement of the Harmonic vendor. The wave generator was hollowed out to make room for the detent clutch and allow the actuator to be much more compact.

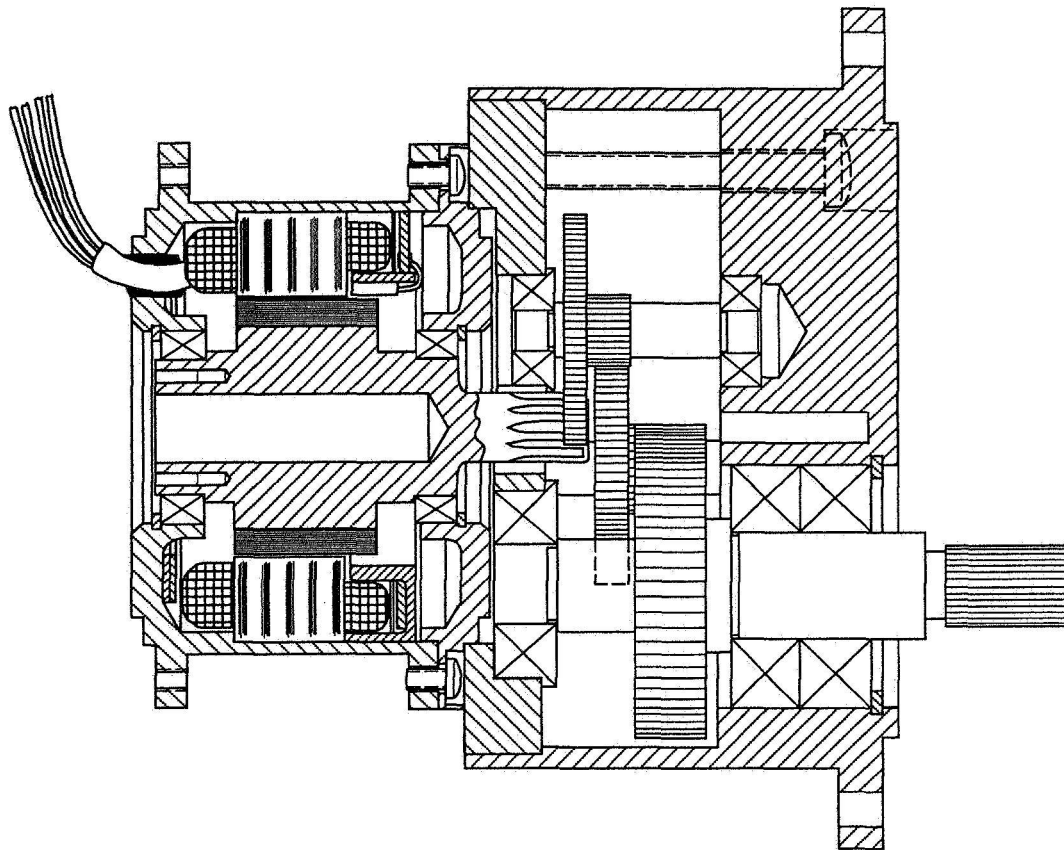


Figure 12 DC Brushless Motor/Gearbox

Table 1 Comparison of Tooth Form Torque Capability

Catalog Rating	Size 40 Standard	Size 50 Standard	Size 40 S-Tooth
Ratchet Limit	745 N-m 6600 in-lb	1410 N-m 12,490 in-lb	1580 N-m* 14,000 in-lb
Momentary Peak Limit	Ratchet Limited	Ratchet Limited	1370 N-m 12,150 in-lb
Mass (unlightened)	3.0 kg	6.0 kg	3.0 kg

* Tested value

Low Temperature Application of Harmonic Gears

Since the harmonic gears are only 30-45% efficient due to their characteristic sliding friction, they are sensitive to temperature effects on lubricant. The LPA motor only produces 0.141 N-m (20 in-oz) at stall. For another application on Mars Pathfinder, a similar motor with half the stall torque was used to drive a size 10 harmonic drive directly, but this actuator would not run below -50°C. The lubricant was changed to a very light grease plate of the Bray 604 low temperature grease, thus correcting the cold operation problems. In comparison, the LPA, with 800 times the input torque applied to a size 40 harmonic gear that was filled to 10-20% of the Bray 601, had no problems to -100°C. The obvious lesson is that, when using smaller, lightweight, low-torque motors, the torque needs to be "preamplified" before being transmitted to the less efficient harmonic gear.

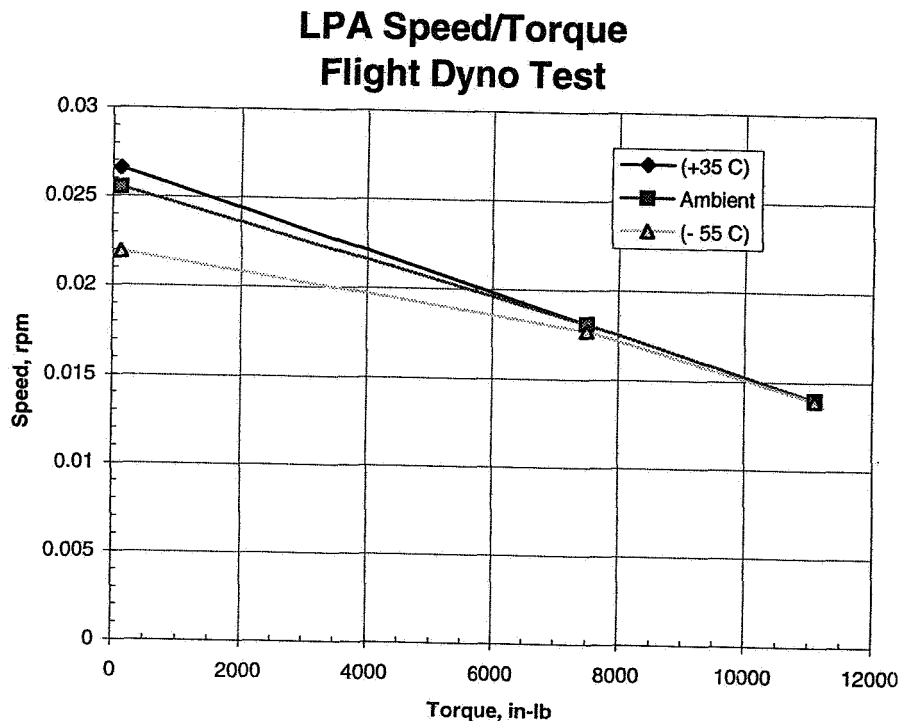
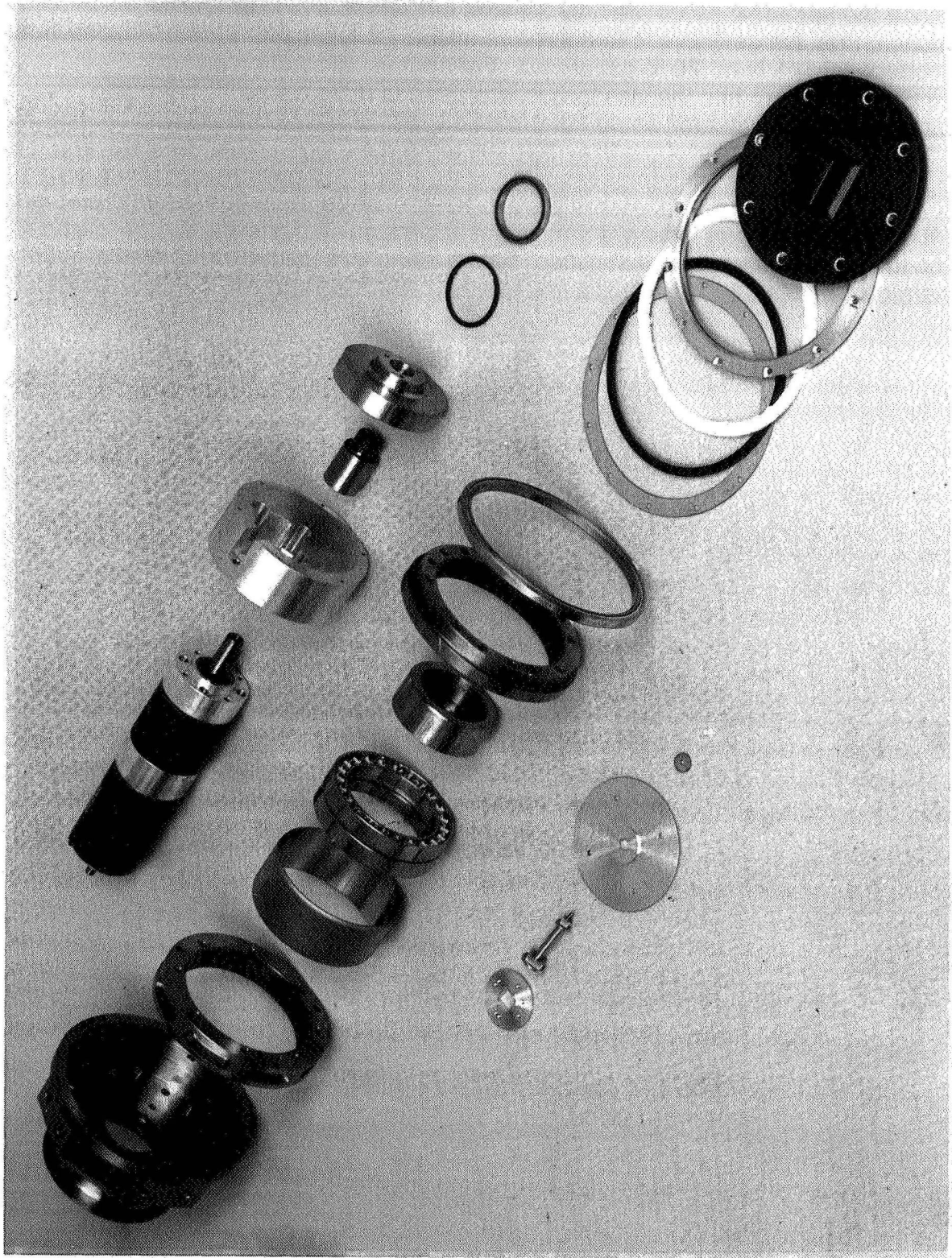


Figure 13 LPA Speed/Torque Curve



**Figure 14 Lander Petal Actuator Exploded View
(with test motor and no clutch)**

Conclusions

The mechanical failure of the Nedox causes us to conclude, once again, that gears under any significant load should not be plated with a hard material. Sub-surface delamination occurs due to the "ceramic-coated banana" condition. Repeated loading and deformation of the gear teeth cause the hard, non-wearing coating to flake off, thus becoming "ground-up razor blades" in the gearbox. For small, lower-torque gearboxes, this proves to be catastrophic.

Bray grease, such as 604 that uses the Brayco 814 oil, is susceptible to mechanical breakdown under moderate loads, especially in conjunction with particles that cause high loading and heat at the asperity level. Greases, such as 600, 601 (with rust preventative), and 602 (with molydisulfide), that use the Brayco 815Z oil are more robust for contact loads but should still avoid high loading or particulate contamination.

Bray 602 tends to be fairly linear in viscosity from ambient temperatures down to -75°C but has geometric increases in viscosity, and hence torque loss, below -75°C .

Electric Discharge Machining (EDM) is an acceptable machining technique for gears, provided that the surface has not been adversely impacted by the process. It appears that the AE power supply enables the EDM process to produce stronger parts with better surface finishes. At this time, until more life testing is possible, it would be prudent to use gears made with the EDM process for limited life applications.

Due to the high startup drag torque of harmonic gears, it is imperative to use other types of gears to "preamplify" the torque before it is transmitted to the harmonic.

Some DC brush motors may be used reliably in a space environment, but they must be free of grease lubrication at low temperatures. Extensive dyno tests on one type of small, DC brush motor proved reliable operation to -75°C , provided that all of the grease was cleaned out.

Acknowledgments

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References

1. Guitrau, E. "EDM and Electrolysis." E & M Engineering. 1995.
2. Castrol, Inc. Specialty Products Division. Product bulletin Braycote 604. 1991.