

JENI Variable Aperture Mechanism Tribology and Life Test

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ABSTRACT

This paper describes the tribological design and life testing of the Variable Aperture Mechanism (VAM) for the NASA supported Jovian Energetic Neutrals and Ions (JENI) instrument to be flown on the ESA Jupiter Icy Moons Explorer (JUICE) mission to Jupiter, Ganymede, Calisto and Europa. JENI employs two VAMs to reduce or eliminate flux from entering the instrument in the same way a lens uses an iris to vary the aperture. The VAM uses two duplex bearing pair assemblies' one mounted face-face and the other back-back. The JENI VAM is designed to be fabricated and assembled at +20°C and operate at -50° to -70°C. The VAM bearings employ steel rings plated with lead, zirconia balls with leaded-bronze separators, provided by ESTL. The gearmotor was originally intended to utilize a hybrid approach with ESTL lead lubricated bearings and proprietary doped MoS2 for the gears and pins. However, the gearmotor bearings were replaced with MoS2 coated bearings provided by ESTL and which were also fitted with PGM-HT cages.

INTRODUCTION

JUICE - JUPITER ICy moons Explorer - is the first large-class mission in ESA's Cosmic Vision 2015-2025 program. Planned for launch in 2022 and arrival at Jupiter in 2029, it will spend at least three years making detailed observations of the giant gaseous planet Jupiter and three of its largest moons, Ganymede, Calisto and Europa. (source: <http://sci.esa.int/juice/>)

Ion and ENA intensities are several orders of magnitude different. Therefore, JENI employs a pair of mechanisms to vary the entrance slit(s) (i.e. stop down the aperture) when high particle intensities might otherwise drive the sensor into saturation, a critical component for the Jovian environment but optional in other potential applications. Both JENI variable aperture mechanisms also have a UV and visible photon filter to allow continued operation in direct sunlight. The JENI variable aperture mechanisms are controlled independently such that, the sunlight filter can be used on one aperture and not on the other, as needed to optimize observations.

VARIABLE APERTURE MECHANISM

DESCRIPTION

JENI employs two VAMs, **Error! Reference source not found.**; to reduce or eliminate flux from entering the instrument in the same way a lens uses an iris to vary the aperture. Each JENI variable aperture mechanism has 11 selectable positions. Position 0 is the closed position. It is also the position that has a calibrated radiation source. This allows the instrument to be functionally checked and calibrated without having to deploy and re-set the launch lock. There is no aperture/slit at position 5. Position 5 blocks the entrance to the instrument with the thickest portion of the slits to provide dark calibrations throughout the mission life. Positions 6 through 10 are associated with apertures Ap-1 through Ap-5 and are covered with a UV and visible light filter. The JENI VAM serves six functions:

- Protect the entrance foil throughout instrument and spacecraft integration and test (I&T)
- Provide acoustic shielding during environmental testing and launch
- Increase JENI's dynamic measurement capability by placing reduced apertures, or slits, in front of the instrument's two entrances
- Provide UV and visible filters to prevent photons from entering the instrument, thus allowing continuous observation, even in direct sunlight
- Block instrument entrances to allow dark calibration throughout the science mission
- Present a calibrated radiation source for instrument calibration throughout the science mission

The VAM uses two duplex bearing pair assemblies; 1) the floating bearing assembly (mounted face-face) for motor attachment allows differential expansion between the instrument housing and the mechanism; 2) the fixed bearing assembly (mounted back-back) anchors the VAM to the instrument. The JENI VAM is designed to be fabricated and assembled at +20°C and operate at -50° to -70°C.

Fixed Bearing Assembly

The JENI variable aperture mechanism is anchored to the instrument with a duplex bearing pair (mounted back-back), **Error! Reference source not found..** A launch lock is also incorporated to prevent rotation during launch and environmental testing. The slits are machined in 80%W-20%Cu material to reduce radiation and particles from entering the instrument as much as possible, resulting in a large un-balanced mass that cannot be prevented from rotating by motor detent torque alone. Therefore, a TiNi P5 pin puller is used to prevent rotation during vibration testing and launch.

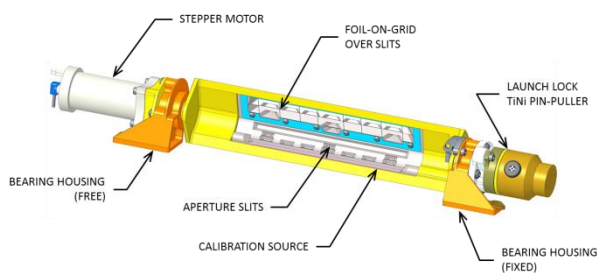


Figure 1 JENI Variable Aperture Mechanism (VAM)

Floating Bearing Design

The JENI variable aperture mechanism is designed to allow the JENI instrument housing (80%W-20%Cu) to expand without influencing the pre-load on the duplex bearing pairs. The floating bearing assembly (mounted face-face) for motor attachment allows differential expansion between the instrument housing and the mechanism by allowing the slit rotor to slip in the bearing bore, **Error! Reference source not found..** The motor output shaft is coupled to the slit rotor with an involute spline coupling that also allows differential expansion between the mechanism and instrument housing.

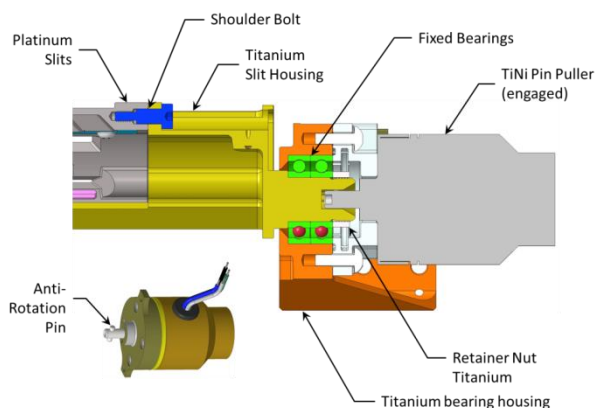


Figure 2 JENI fixed bearing assembly.

SOLID LUBRICATION FOR JENI

TRIBOLOGICAL COMPONENTS

Solid lubricants have become well established for use in space. They provide the only viable means of lubrication where oils and greases cannot be used, for example at temperature extremes or where there is the need to avoid molecular contamination. Two solid lubricants are employed in the JENI instrument, these being thin films of lead and MoS₂, both applied by physical vapor deposition (PVD) processes at ESTL. The following table provides some additional information.

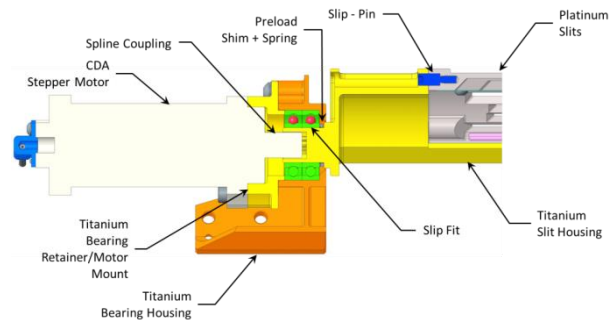


Figure 3 JENI Floating Bearing Assembly Allows Differential Expansion Between the Instrument Housing and the Mechanism.

If MoS₂-coated components are operated in an environment with humidity levels above 5% R_H then the MoS₂ coating degrades and the lifetime of the lubricant coating decreases. Any operational cycles must be performed under a dry nitrogen purge of less than 15 ppm moisture content (~0.05%R_H) and kept to a minimum. In the intermediate range of humidity, the effects on life are not well documented. The following Figure shows as a function of relative humidity the preferred operational environment for MoS₂.

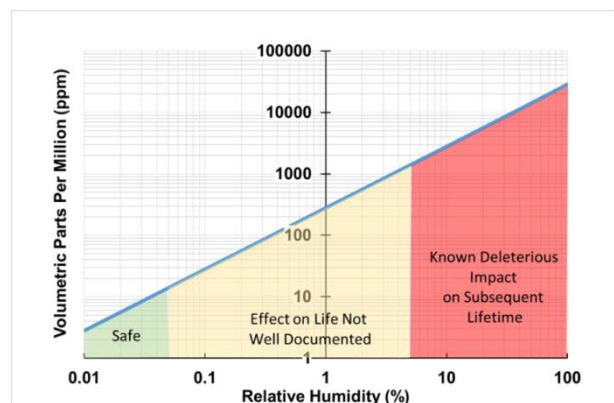


Figure 4 Definition of Safe, Marginal (less well documented, although recent work at ESTL indicates that up to 3% Rh could be safe for operation) and Known Deleterious Humidity Conditions for MoS₂ Testing In Nitrogen

For PVD lead lubricated bearings having a lead-bronze cage, limited operation in cleanroom air is permissible.

Up to 105 revs have been carried out at low speed. (<100rpm). However, the torque and cage wear can be expected to increase during this type of operation. Note that this effect will also occur in nitrogen. After bearing operation in air or in nitrogen of up to ~105 revs equivalent, nominal in-vacuum operational behaviour will usually be recovered after a period of in-vacuum running (from a few revs to several thousand revolutions). There are no indications that operation in air or nitrogen will impact the subsequent in-vacuum lifetime of lead-lubricated bearings.

To ensure that the optimum performances of thin film lubricants applied by PVD processes, particular precautions relating to storage and handling must be observed.

Gearmotor Tribology

“In applications involving rolling element bearings, proper attention to cage design and materials selection is essential in order to ensure reliable, long term bearing performance” Gary Hughes, product engineering - manager at The Barden Corporation¹

The primary purpose of the cage is to maintain uniform ball spacing. Cages are typically piloted by the balls in low to medium speed applications. The cages are typically guided by the inner or outer ring lands which improves stability during operation. Deep groove bearings are typically assembled with the balls grouped together and then uniformly separating the balls and assembling the cage. Angular contact bearings can be assembled with solid machined cages by differentially heating one ring which allows the ball set and cage to pass over a restraint on the bearing lands (ball dam).

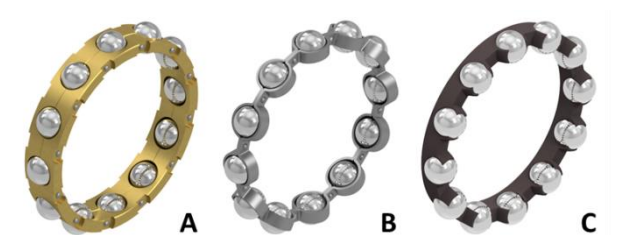


Figure 5 Deep Groove Ball Bearing Cages. A) Multi-piece machined bronze cage. B) Riveted pressed steel cage. C) Single piece snap-in cage. Photo credit: <http://de.aec.com/produkte/kugellager/schraegkugellager/einreihige-schraegkugellager/>

The CDA Intercorp motors were originally ordered with PVD lead lubricated bearings. However, the motor and planetary gear reduction assemblies use deep groove bearings and lead-bronze cages could not be machined and de-burred adequately to be usable. The bearings were too small to use a multi-piece bronze cage assembly

and a snap in type cage design was employed. Unfortunately, the cages were subsequently found to be too small and fragile to adequately remove burrs present after the machining process and there were concerns that these burrs could potentially become detached and contaminate the bearings, leading to torque anomalies.

Bearings

The motor and planetary gear stage bearings were provided by CDA coated with ESTL’s MoS₂ coating. ESTL replaced the standard cages with cages manufactured from PGM-HT which were provided by JPM of Mississippi.

Table 1 JENI Variable Aperture Mechanism Bearing Materials and Tribology

	Variable Aperture Mechanism	Stepper Motor Bearings	Planetary Bearings
Materials			
Rings	Cronidur®	440C	440C
Balls	Zirconia	440C	440C
Cages	lead bronze	PGM-HT*	PGM-HT*
Lubrication			
Dry film	PVD Lead	MoS ₂	MoS ₂

THERMAL ENVIRONMENT

The JENI variable aperture mechanism life test was conducted in a space simulation chamber with a base pressure less than $\leq 10^{-6}$ Torr at the temperatures shown in Figure 6.

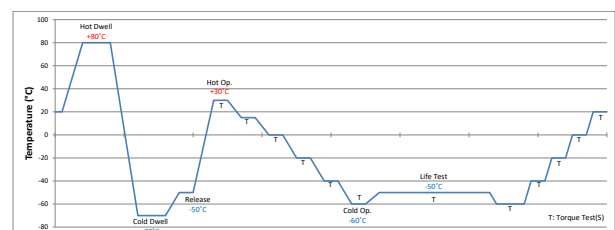


Figure 6 JENI Variable Aperture Mechanism Qualification and Life Test Thermal Environment.

JENI SHUTTER TORQUE TESTS

The JENI VAM conducted torque tests during transitions from hot-to-cold and cold-to-warm, Figure 6. This test will determine the torque vs. temperature pre and post life test.

Required Life Test Cycles

The JENI VAM life test cycles were calculated per ESA mechanism life test requirements, Table 2.

Table 2 The JENI Variable Aperture Mechanism Life Test Cycles Calculation.

JENI Shutter Life Test Duration					
Ground Operations			Flight Operations		
400 test motions/cycles			37,161 test motions/cycles		
Motions	Test Factor	Total	Motions	Test Factor	Total
1 - 1000	x	4	1 - 10	x	10
		1600	11 to 1,000	x	4
			1,001 to 100,000	x	2
Total		1600	Total		76,382

Life Test Cycles

An expected operational sequence was developed “test like we fly, fly like we test” philosophy. The shutter bearings can NOT make a full revolution. Small oscillatory motions are often more detrimental to bearing wear and life than continuous rotations. Two sequences were designed to use the “most likely” scenario of small motions and a tour of all positions, *Table 4*, *Table 5* and *Figure 7*.

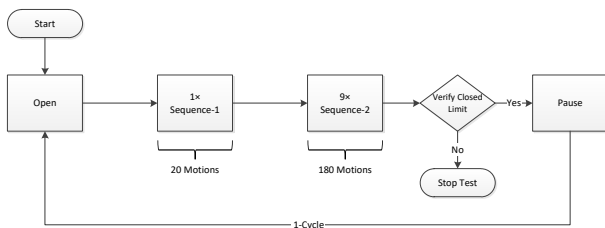


Figure 7 Automated Life Test Cycles.

Torque margins

Torque margins were measured at multiple temperatures, Figure 8, prior to, during and post life-test. Torque margins were established by incrementally reducing the voltage to the motor until the test pattern could not be completed without skipped steps.

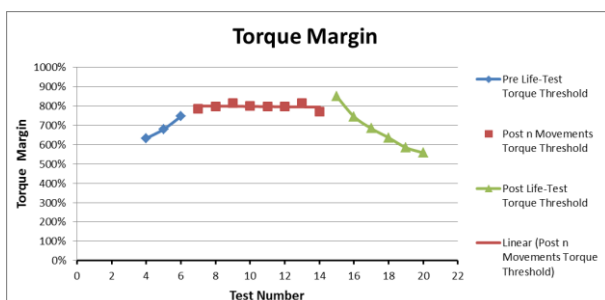


Figure 8 JENI Variable Aperture Mechanism Torque Threshold Margin Before, During, and After Life Test.

POST LIFE TEST ASSESSMENT

Post Life Test Mechanism Inspection

Following the life test, the VAM was disassembled for inspection. The bearings, Figure 9 and Figure 10, were considered to be in pristine condition and therefore, were not disassembled. The life test motor was re-assembled and returned to the mechanism which was also re-assembled and used for additional instrument development.

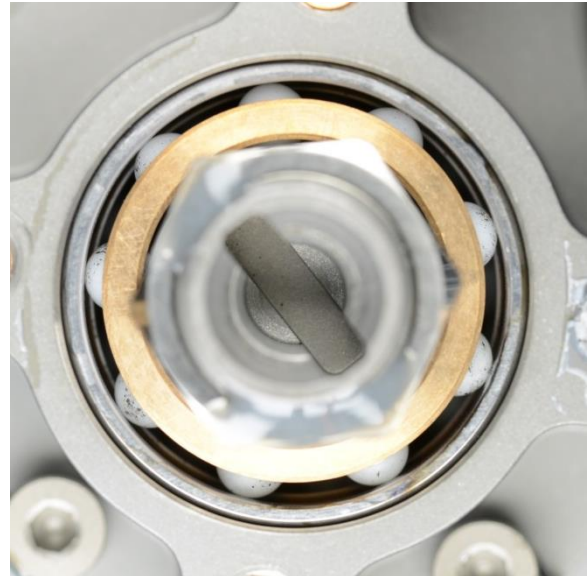


Figure 9 Fixed Bearings (back-back) Following 80,000 Life Cycles.



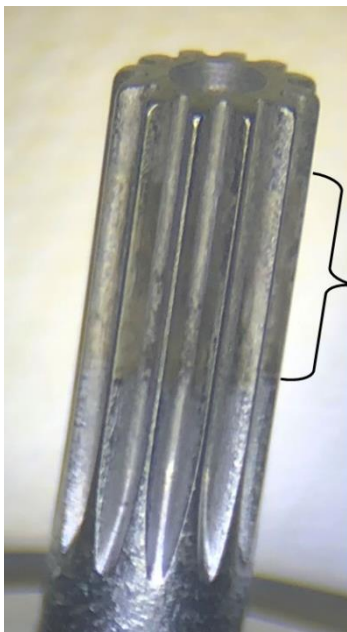
Figure 10 Floating Bearings (face-face) Following 80,000 Life Cycles.

Post Life Test Gearmotor Inspection

The gearmotor was returned to the vendor for complete disassembly and documentation of all lubricated surfaces. A sample of the gearmotor gears and bearings are shown in Figure 11 and Figure 12.



Figure 11 High Speed Stage Bearing in Very Good Condition Showing No Signs of Wear and Good Lubrication Coverage. High Speed Planet Gears Show No Presence of Wear Debris.



Low speed
planet gears
wear section

Figure 12 Low Speed Planetary Sun Gear Showing Virtually No Lubrication Wear.

LIFE TEST CONCLUSION AND SUMMARY

The mechanism completed life testing with 82,824 motions and the gearmotor executed 8,128,197 steps. The JENI variable aperture mechanism successfully completed life testing and has demonstrated:

- Survivability in all expected launch and space environments
- More than adequate torque margin in all expected space environments
- Life span capable of exceeding 80,000 motions
- Can reliably position the slit throughout its expected life
- No excessive wear or anomalies in post life test disassembly inspection

APPENDIX-1 Figures & Tables

Table 3 PVD Lead and MoS₂ Films

Lubricant Coating	Thickness (µm)	Temp range in vac (K)	Friction coefficient in vac/air	Lifetime in vac	Advantages	Disadvantages
PVD (Sputtered) MoS ₂	0.5 to 1.0	4 to 700	V low/moderate	Moderate and good if used with PGM-HT cages	Very low friction in vacuum	Lifetime reduced if operated in air
PVD (Sputtered lead)	0.2 to 0.5	4 to 550	Moderate/moderate	High – use with leaded bronze cages	Long lifetime. Recovers after operation in air	Torque increases in air or nitrogen

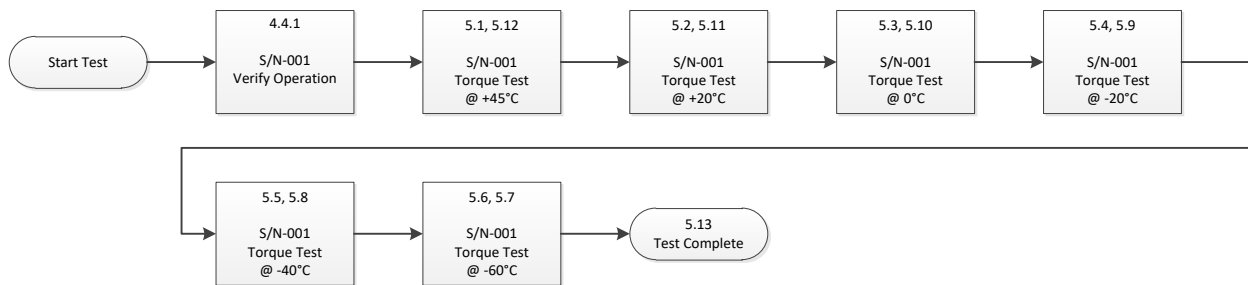


Figure 13 Torque Margin Threshold Tests Throughout Possible Operating Environment.

Table 4 Life Test Sequence-1. Tour of All Positions.

Movement	Aperture		Position		Steps	Dir.	Rotations	
	From	To	From	To			CW	CCW
1	Closed-Source-Cal	Wide-Slit	0	4	214	CW	17.8	0.0
2	Wide-Slit	Narrow-Slit	4	1	-169	CCW	0.0	-14.1
3	Narrow-Slit	Wide-Slit	1	4	169	CW	14.1	0.0
4	Wide-Slit	Narrow-Slit	4	1	-169	CCW	0.0	-14.1
5	Narrow-Slit	7-Slits	1	2	51	CW	4.3	0.0
6	7-Slits	3-Slits	2	3	51	CW	4.3	0.0
7	3-Slits	7-Slits	3	2	-51	CCW	0.0	-4.3
8	7-Slits	Narrow-Slit	2	1	-51	CCW	0.0	-4.3
9	Narrow-Slit	Wide-Slit-Foil	1	10	507	CW	42.3	0.0
10	Wide-Slit-Foil	Narrow-Slit-Foil	10	8	-115	CCW	0.0	-9.6
11	Narrow-Slit-Foil	7-Slits-Foil	8	9	51	CW	4.3	0.0
12	7-Slits-Foil	3-Slits-Foil	9	7	-102	CCW	0.0	-8.5
13	3-Slits-Foil	1-Slit-Foil	7	6	-51	CCW	0.0	-4.3
14	1-Slit-Foil	3-Slits-Foil	6	7	51	CW	4.3	0.0
15	3-Slits-Foil	7-Slits-Foil	7	9	102	CW	8.5	0.0
16	7-Slits-Foil	Narrow-Slit-Foil	9	8	-51	CCW	0.0	-4.3
17	Narrow-Slit-Foil	Wide-Slit-Foil	8	10	115	CW	9.6	0.0
18	Wide-Slit-Foil	Narrow-Slit-Foil	10	8	-115	CCW	0.0	-9.6
19	Narrow-Slit-Foil	Dark-Cal	8	5	-154	CCW	0.0	-12.8
20	Dark-Cal	Closed-Source-Cal	5	0	-283	CCW	0.0	-23.6

Table 5 Life Test Sequence-2. Back-and-Forth to Most Likely Positions.

Movement	Aperture		Position		Steps	Dir.	Rotations	
	From	To	From	To			CW	CCW
1	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
2	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
3	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
4	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
5	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
6	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
7	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
8	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
9	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
10	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
11	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
12	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
13	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
14	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
15	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
16	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
17	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
18	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2
19	Narrow-Slit	1-Slit-Foil	1	6	290	CW	24.2	0.0
20	1-Slit-Foil	Narrow-Slit	6	1	-290	CCW	0.0	-24.2

Table 6 Threshold Voltage and Torque Margin Pre, During, and Post Life Test.

	#	Test	Temp	Winding Resistance	Pressure ×10 ⁻⁸ Torr	Supply Volts (no skip)	Motor Volts	Threshold Current ¹ (mA)	Available Current @ 15V ²	Output Torque Current Margin ³	Overall Margin ⁴
Pre Life-Test Torque Threshold	1	+45°C		122							
	2	+20°C		111							
	3	0°C		102							
	4	-20°C	-22	94	12	6.4	2.05	44	319	733%	633%
	5	-40°C	-40	86	11	6.4	1.92	45	349	779%	679%
Post n Movements Torque Threshold	6	-60°C	-60	75	9.8	6.5	1.77	47	400	846%	746%
	7	10,000	-54	79	8.1	6	1.69	43	381	886%	786%
	8	20,000	-53	79	6.7	5.9	1.67	42	379	897%	797%
	9	30,000	-54	79	6	5.8	1.64	42	381	916%	816%
	10	40,000	-54	79	6	5.9	1.67	42	381	901%	801%
	11	50,000	-53	79	5.8	5.9	1.67	42	379	897%	797%
	12	60,000	-53	79	6.3	5.9	1.67	42	379	897%	797%
	13	70,000	-54	79	5.8	5.8	1.64	42	381	916%	816%
Post Life-Test Torque Threshold	14	80,000	-54	79	5.9	6.1	1.72	44	381	871%	771%
	15	-60°C	-63	75	5.9	5.8	1.58	42	402	951%	851%
	16	-40°C	-42	84	6	6	1.77	42	357	846%	746%
	17	-20°C	-20	94	6.4	6	1.91	41	321	784%	684%
	18	0°C	1	103	7.8	6	2.04	40	292	736%	636%
	19	+20°C	22	112	9.8	6.1	2.19	39	268	685%	585%
	20	+45°C	46	123	13	6	2.28	37	245	658%	558%