Introduction to *Spacecraft Mechanisms:*
ECSS-E-ST-33-01C

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15/9/2021

Content

Terms and Definitions

→ What is a mechanism? Which disciplines are involved?

Scope

→ When is the standard applicable? How to use it?

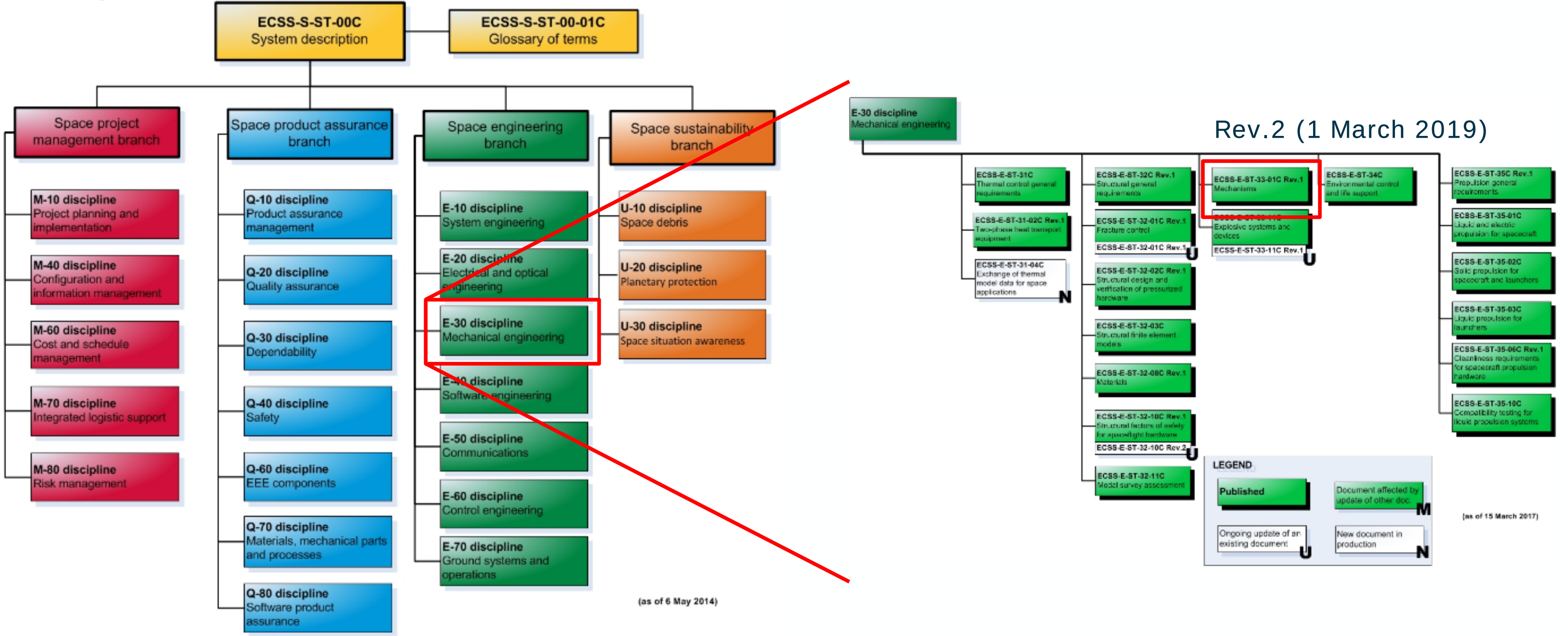
Requirements

→ Design (dimensioning, material selection, etc.)

→ Verification (analysis and test)

Where to find our standards?

ECSS Disciplines



ECSS-S-ST-00C
System description

ECSS-S-ST-00-01C
Glossary of terms

Space project management branch
- **M-10 discipline** Project planning and implementation
- **M-40 discipline** Configuration and information management
- **M-60 discipline** Cost and schedule management
- **M-70 discipline** Integrated logistic support
- **M-80 discipline** Risk management

Space product assurance branch
- **Q-10 discipline** Product assurance management
- **Q-20 discipline** Quality assurance
- **Q-30 discipline** Dependability
- **Q-40 discipline** Safety
- **Q-60 discipline** EEE components
- **Q-70 discipline** Materials, mechanical parts and processes
- **Q-80 discipline** Software product assurance

Space engineering branch
- **E-10 discipline** System engineering
- **E-20 discipline** Electrical and optical engineering
- **E-30 discipline** Mechanical engineering
- **E-40 discipline** Software engineering
- **E-50 discipline** Communications
- **E-60 discipline** Control engineering
- **E-70 discipline** Ground systems and operations

Space sustainability branch
- **U-10 discipline** Space debris
- **U-20 discipline** Planetary protection
- **U-30 discipline** Space situation awareness

(as of 6 May 2014)

E-30 discipline
Mechanical engineering

Rev.2 (1 March 2019)

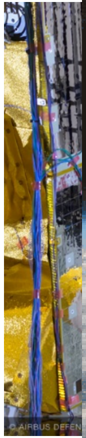
- **ECSS-E-ST-31C** Thermal control general requirements
- **ECSS-E-ST-31-02C Rev.1** Two-phase heat transport equipment
- **ECSS-E-ST-31-04C** Exchange of thermal model data for space applications N
- **ECSS-E-ST-32C Rev.1** Structural general requirements
- **ECSS-E-ST-32-01C Rev.1** Fracture control / ECSS-E-ST-32-01C Rev.1 U
- **ECSS-E-ST-32-02C Rev.1** Structural design and verification of pressurized hardware
- **ECSS-E-ST-32-03C** Structural finite element models
- **ECSS-E-ST-32-08C Rev.1** Materials
- **ECSS-E-ST-32-10C Rev.1** Structural factors of safety for spaceflight hardware / ECSS-E-ST-32-10C Rev.2 U
- **ECSS-E-ST-32-11C** Model survey assessment
- **ECSS-E-ST-33-01C Rev.1** Mechanisms
- Explosive systems and devices / ECSS-E-ST-33-11C Rev.1 U
- **ECSS-E-ST-34C** Environmental control and life support
- **ECSS-E-ST-35C Rev.1** Propulsion general requirements
- **ECSS-E-ST-35-01C** Liquid and electric propulsion for spacecraft
- **ECSS-E-ST-35-02C** Solid propulsion for spacecraft and launchers
- **ECSS-E-ST-35-03C** Liquid propulsion for launchers
- **ECSS-E-ST-35-06C Rev.1** Cleanliness requirements for spacecraft propulsion hardware
- **ECSS-E-ST-35-10C** Compatibility testing for liquid propulsion systems

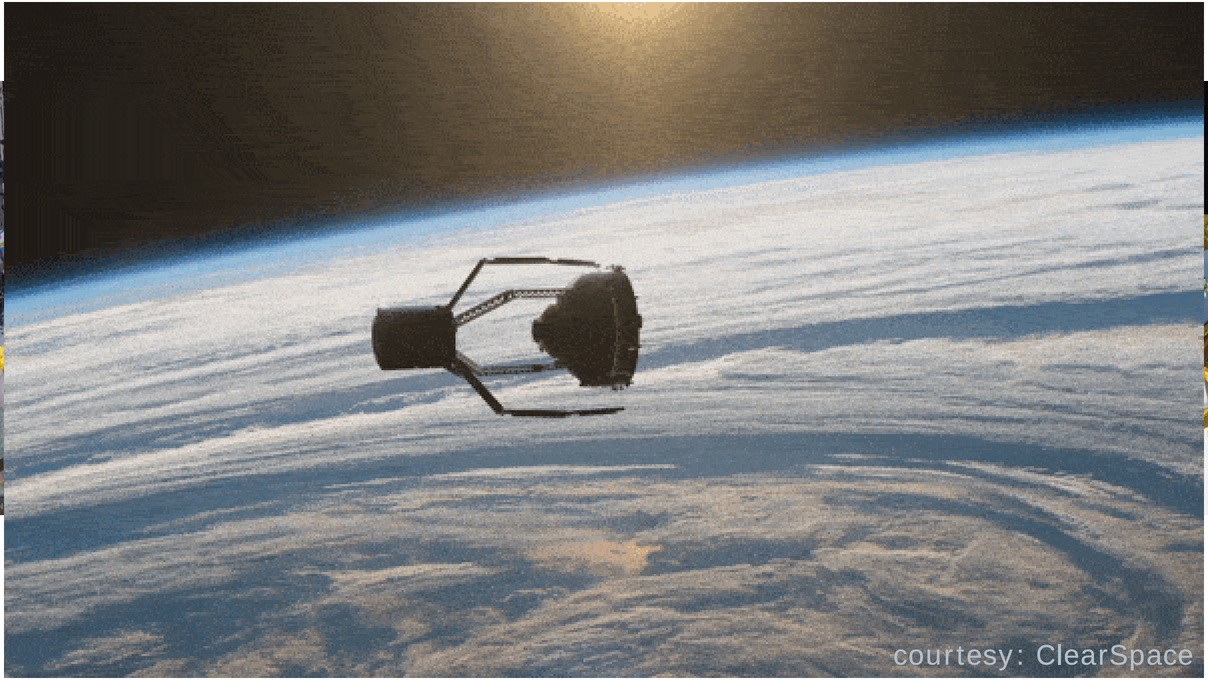
LEGEND
- **Published**
- Document affected by update of other doc. M
- Ongoing update of an existing document U
- New document in production N

(as of 15 March 2017)

Spacecraft Mechanisms

"Assembly of components that are linked together to intentionally **enable a relative motion**."




courtesy: ClearSpace

Spacecraft Mechanisms

Actuators	e.g. electric motor, spring, SMA, voice coil, piezo-electric, etc.
Transmission	e.g. shafts, couplings, gears, etc.
Bearings	e.g. ball bearings, journal bearings, etc.
Sensors	e.g. optical, magnetic, mechanical, etc.
Controller	open / closed loop, uncontrolled

Spacecraft Mechanisms

tribology

discipline that deals with the design, friction, wear and lubrication of interacting surfaces in relative motion to each other

lubrication

use of specific material surface properties or an applied material between two contacting or moving surfaces in order to reduce friction, wear or adhesion

ECSS-E-ST-33-01C Rev.2

…specifies the **requirements** applicable to the

- concept definition
- development
- design
- production
- verification
- in-orbit operation

of space mechanisms on spacecraft and payloads

in order to **meet the mission performance requirements**.

Normative references

ECSS-S-ST-00-01	ECSS system — Glossary of terms
ECSS-E-ST-10-02	Space engineering – Verification
ECSS-E-ST-20	Space engineering – Electrical and electronic
ECSS-E-ST-20-06	Space engineering – Spacecraft charging
ECSS-E-ST-20-07	Space engineering – Electromagnetic compatibility
ECSS-E-ST-31	Space engineering – Thermal control general requirements
ECSS-E-ST-32	Space engineering – Structural
ECSS-E-ST-32-01	Space engineering – Fracture control
ECSS-E-ST-32-10	Space engineering – Structural factors of safety for spaceflight hardware
ECSS-E-ST-33-11	Space engineering – Explosive systems and devices
ECSS-Q-ST-30	Space product assurance - Dependability
ECSS-Q-ST-40	Space product assurance – Safety
ECSS-Q-ST-70	Space product assurance – material, mechanical part and process
ECSS-Q-ST-70-36	Space product assurance – Material selection for controlling stress corrosion cracking
ECSS-Q-ST-70-37	Space product assurance – Determination of the susceptibility of metals to stress corrosion cracking
ECSS-Q-ST-70-71	Space product assurance – Data for selection of space materials and processes
ISO 76 (2006)	Rolling bearings – Static load rating
ISO 128 (1996)	Technical drawings
ISO 677 (1976)	Straight bevel gears for general engineering and for

General Requirements: Units

All units to be used: SI

E.g. kinematic viscosity

= [St] Stokes

= $10^{-4}\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$

General Requirements: Maintainability

→ Mechanisms shall be designed to be **maintenance free**

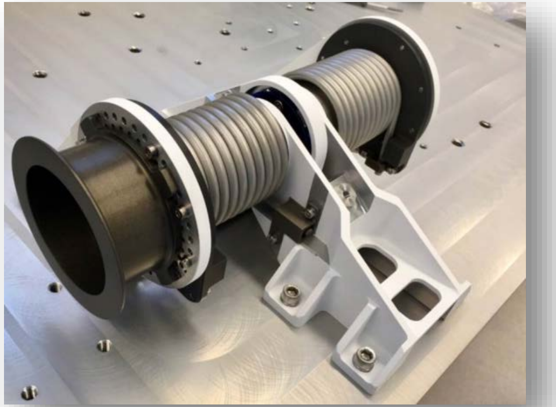
→ If maintenance is required, it shall be **approved** by the customer and **procedures** shall be provided

General Requirements: Redundancy

- single point failure modes shall be identified

- single points of failure should be eliminated by **redundant components**

- **active elements** of mechanisms shall be redundant, such as sensors, motor windings, brushes, actuators, switches and electronics



Courtesy of Sener (PL)

http://www.componeticsinc.com/

Mission Environment

The mechanism engineering shall consider **every mission phase** identified for the specific space programme, i.e.:

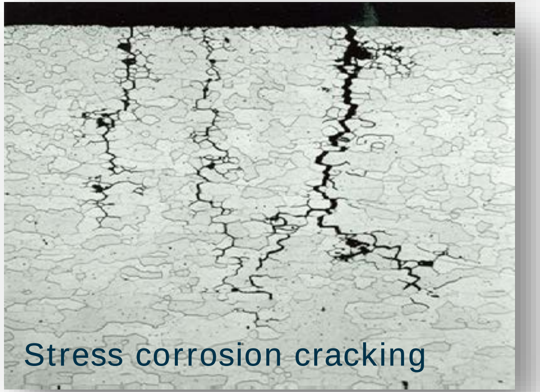
- → Assembly and integration (humidity, oxygen)
- → Testing (1 g environment, additional resistive loads)
- → Storage (long term effects)
- → Handling and shipment (loads, accessibility)
- → Launch (mechanical loads)
- → In-orbit operation / hibernation (operational loads, thermal, radiation, EMC, life, etc.)

Material selection

… shall be performed in conformance with **ECSS-Q-ST-70 (Materials)**:

- → Corrosion
- → **Galvanic corrosion (→ dissimilar metals)**
- → **Stress corrosion cracking (e.g. 440C, Cronidur X30)**
- → Fungus protection
- → Flammable, toxic and unstable materials
- → Induced emissions (stray light protection)
- → Radiation
- → Atomic oxygen
- → Fluid compatibility

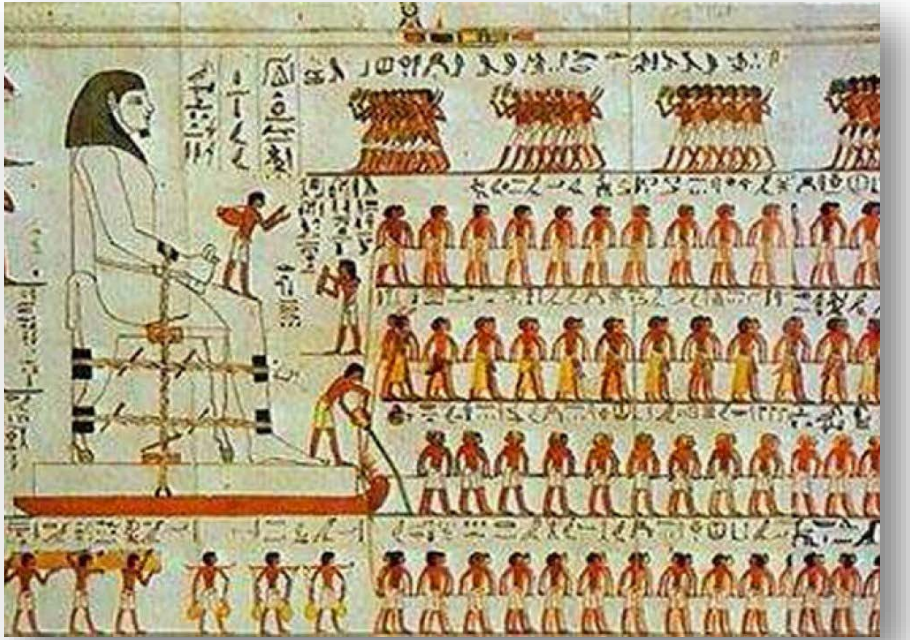

Galvanic corrosion


Stress corrosion cracking

Design Requirements: Tribology

Mechanisms shall:

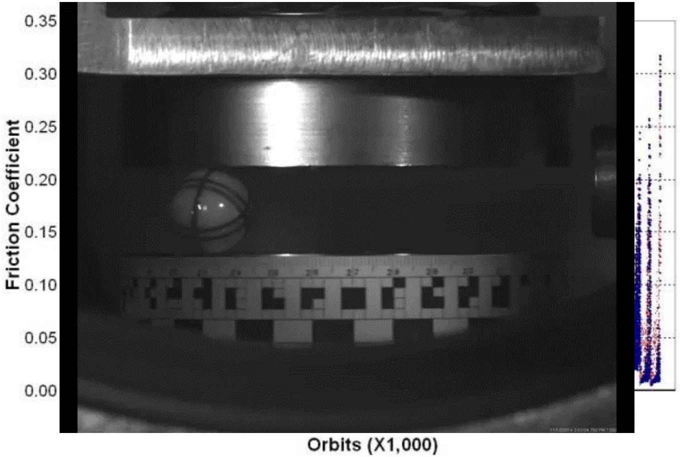
- be designed with a **lubrication function** between surfaces
  - → Reduce friction and wear
  - → Increase lifetime
- use only lubricants **qualified for the mission**
  - → Temperatures, ambient pressure, contact pressure, number of cycles, lifetime, relative velocity etc.

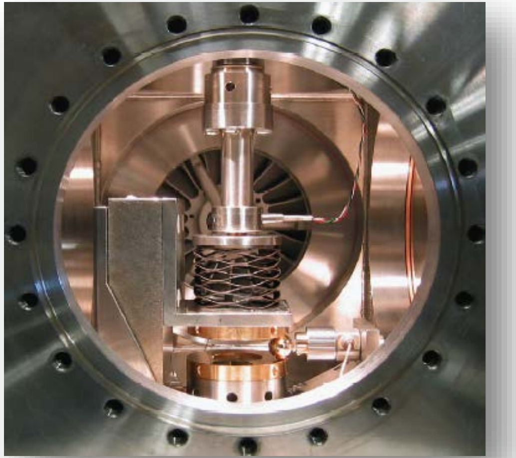


Design Requirements: Tribology (cont'd)

Qualification of lubricant via:

- → Heritage or dedicated lifetest (see slides 51 ff.)
- → Component level: bearing / gear test rigs, Pin on disc (POD), Spiral orbit tribometer (SOT)





SOT device by ESTL

European Space Tribology Laboratory (ESTL):

- → operates test facilities
- → has data base on qualified lubricants
- → provides consultancy

www.esrtechnology.com

Design Requirements: Dry Lubrication

... preferred for operation in **high temperature**, at **low speeds**, **low number of operational cycles**, when **cleanliness** is an issue (e.g. optical payloads have problems with condensation)

... applied through processes such as sputtering, vapor deposition etc.

... e.g. MoS_2, WS_2, graphite, PTFE, lead

→ Samples of representative material […] shall be co-deposited in each process with the flight components so that verification checks can be performed;

→ The thickness and adhesion of the lubricant on samples shall be verified;

Design Requirements: Fluid Lubrication

... for **high speed**, **low friction** and **high number of operational cycles**

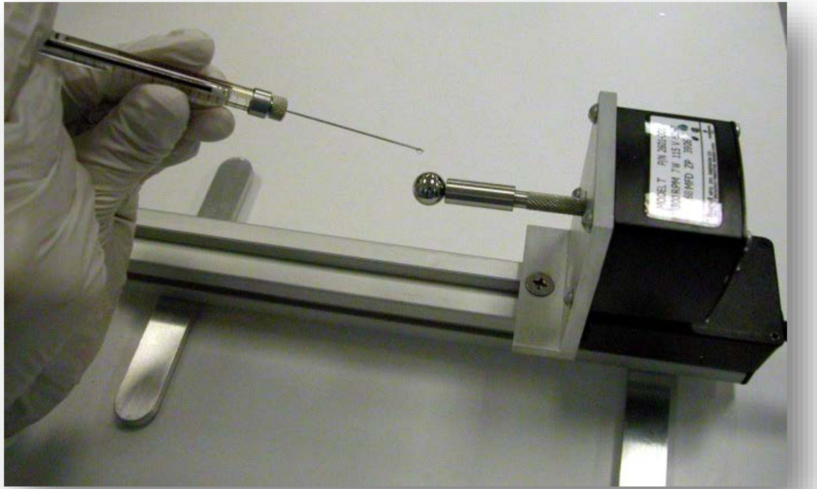
... wide range of space qualified hydrocarbon and synthetic oils

→ The **quantity** of lubricant used shall be determined.

→ **Outgassing**, **creep** and absorption shall be taken into account (including **ground effects**, i.e. gravity)

→ For rules on outgassing (total / relative mass loss, collected volatile condensable materials):

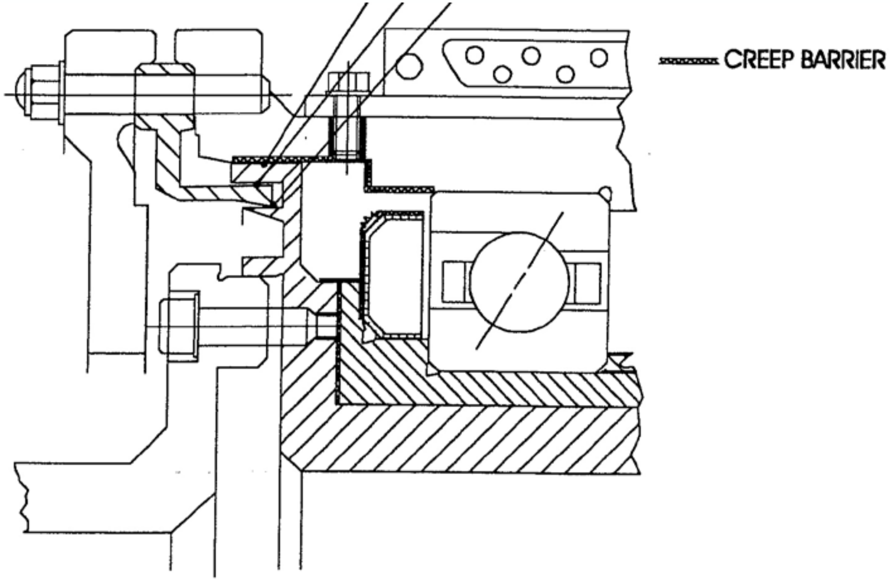
→ **ECSS-Q-ST-70-02**



Courtesy of ESTL

Design Requirements: Anti-creep barriers

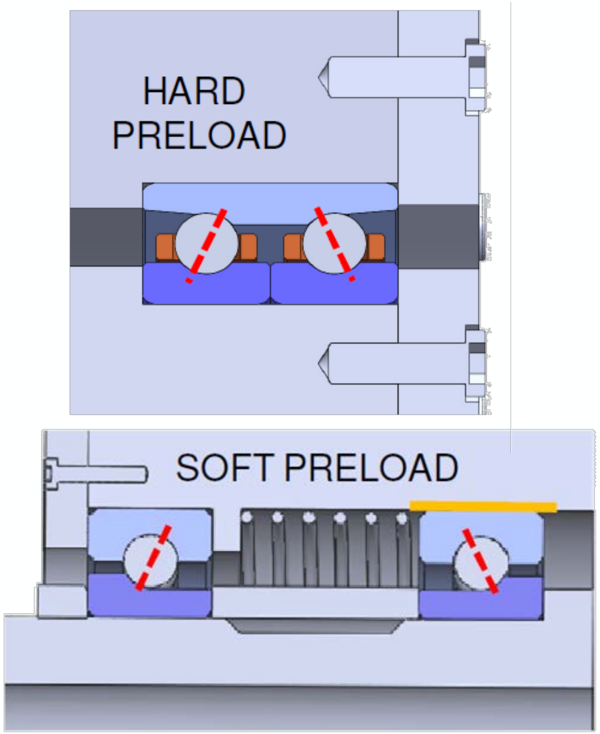
- → **avoid migration** of fluid lubricants to the internal/external sensitive equipment;
- → causes a **change of the lubricant amount** on the parts to be lubricated;
- → **integrity** of the anti-creep barrier shall be verifiable by indicators.



Courtesy of ESTL

Design Requirements: bearing preload

- → Ball bearings shall be preloaded to **withstand mechanical environment**;
- → Preload **calculation** shall be made available
- → Preloading should be applied by **solid or flexible** preload;
- → Preload **should be measured** after assembly;
- → preload should be confirmed **after running-in**;

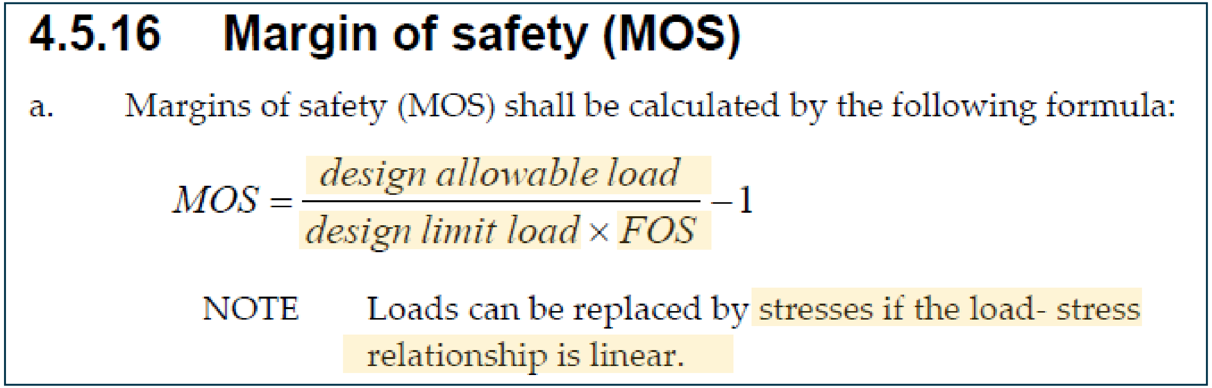


Courtesy of ESTL

Design Requirements: structural dimensioning

Mechanisms shall be designed with a **positive margin of safety** against yielding and against ultimate under all environmental conditions and operational load conditions

→ **ECSS-E-ST-32**
(structures):



4.5.16 Margin of safety (MOS)

a. Margins of safety (MOS) shall be calculated by the following formula:

$$MOS = \frac{design\ allowable\ load}{design\ limit\ load \times FOS} - 1$$

NOTE Loads can be replaced by stresses if the load- stress relationship is linear.

→ **ECSS-E-ST-32-10**
(factors of safety):

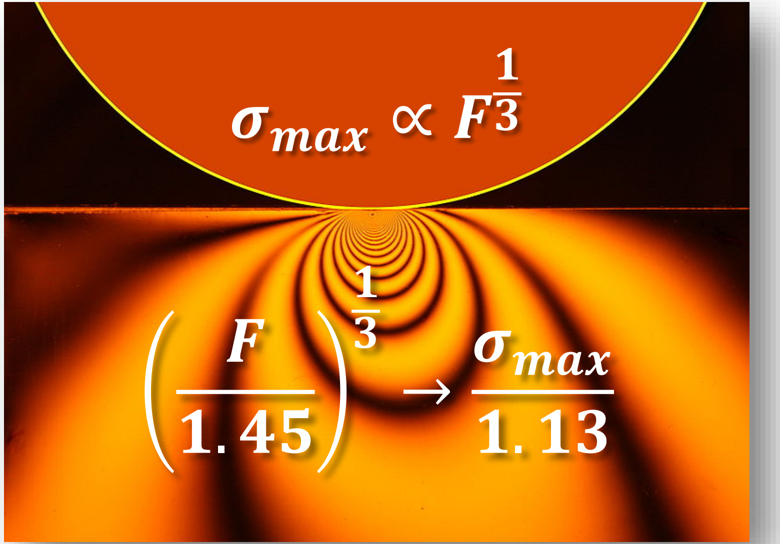
$$FOS_Y = 1.1$$

$$FOS_U = 1.25$$

(typical values)

Design Requirements: ball bearings

- → shall be sized with respect to the maximum allowable **peak hertzian contact stress**;
- → For the evaluation of the peak hertzian contact stress, a minimum **factor of 1.45** shall be applied to the design limit load;



$$\sigma_{max} \propto F^{\frac{1}{3}}$$

$$\left(\frac{F}{1.45}\right)^{\frac{1}{3}} \rightarrow \frac{\sigma_{max}}{1.13}$$

According to **ISO76** (static load rating):

→ axial / radial static load capacity ≙ load producing a maximum contact stress of

4200 MPa (for hardened steels, e.g. SAE 52100)

4000 MPa (for stainless steels, e.g. 440C)

Design Requirements: motorisation

Actuators shall be sized to provide ***torques*** / ***forces*** in conformance with:

$$\boxed{T_{min} = 2 \cdot (1.1 \cdot I + 1.2 \cdot S + 1.5 \cdot H_M + 3 \cdot F_R + 3 \cdot H_Y + 3 \cdot H_A + 3 \cdot H_D) + 1.25 \cdot T_D + T_L}$$

$$\boxed{T_{min} \geq 2 \cdot \sum_i \left(k_i \cdot T_{res,i}\right) + T_L + 1.25 \cdot T_D}$$

- throughout the operational **lifetime** (ageing, lubricant degradation, creep, etc.)
- over the full **range of travel**
- worst case **environmental and operational conditions** (temperatures, mechanical loads)

Design Requirements: motorisation (cont'd)

Actuators shall be sized to provide ***torques*** / ***forces*** in conformance with:

$$T_{min} = 2 \cdot (1.1 \cdot I + 1.2 \cdot S + 1.5 \cdot H_M + 3 \cdot F_R + 3 \cdot H_Y + 3 \cdot H_A + 3 \cdot H_D) + 1.25 \cdot T_D + T_L$$

$$T_{min} \geq 2 \cdot \sum_i \left(k_i \cdot T_{res,i}\right) + T_L + 1.25 \cdot T_D$$

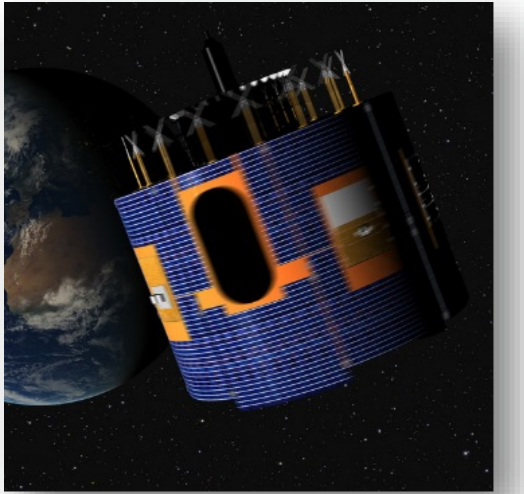
T_L: Deliverable **output torque of the mechanism** when specified by customer

T_D: **inertial resistance torque** caused by the worst-case acceleration function specified by the customer (i.e. customer specifies a motion rather than a torque)

Design Requirements: motorisation (cont'd)

Minimum uncertainty factors for **loss terms:**

Resistive force or torque contributor	Symbol	Theoretical Factor	Measured Factor
Inertia	I	1,1	1,1
Spring	S	1,2	1,1
Magnetic effects	H_M	1,5	1,1
Friction	F_R	3	1,5
Hysteresis	H_Y	3	1,5
Others (e.g. Harness)	H_A	3	1,5
Adhesion	H_D	3	3



→ **$I \neq T_D$**, but resistive inertia load due to acceleration of mechanism itself (e.g. spinning spacecraft!)

→ **S ≠ actuation torque**, but resistive spring load (e.g. latch)

Design Requirements: motorisation (cont’d)

If actuation force / torque is supplied by a spring:

- → springs shall be redundant (e.g. 1:2 or 2:3 redundancy)
- → actuation torque / force shall be multiplied by an uncertainty **factor of 0.8** (→ only if ageing measurements are not available)

If actuation force / torque is supplied by an electric motor:

- → Worst case actuation torque / force shall be **measured at operating conditions** (i.e. at representative temperatures, pressures, speeds, loads etc.)

Actuation forces / torques supplied by **devices whose primary function is not to provide actuation** (e.g. harness) shall not be taken into account

Exercise: Motorisation I

reaction wheel

$$T_{min} \geq 2 \cdot \sum_{i} \left(k_i \cdot T_{res,i}\right) + T_L + 1.25 \cdot \cancel{T_D}$$

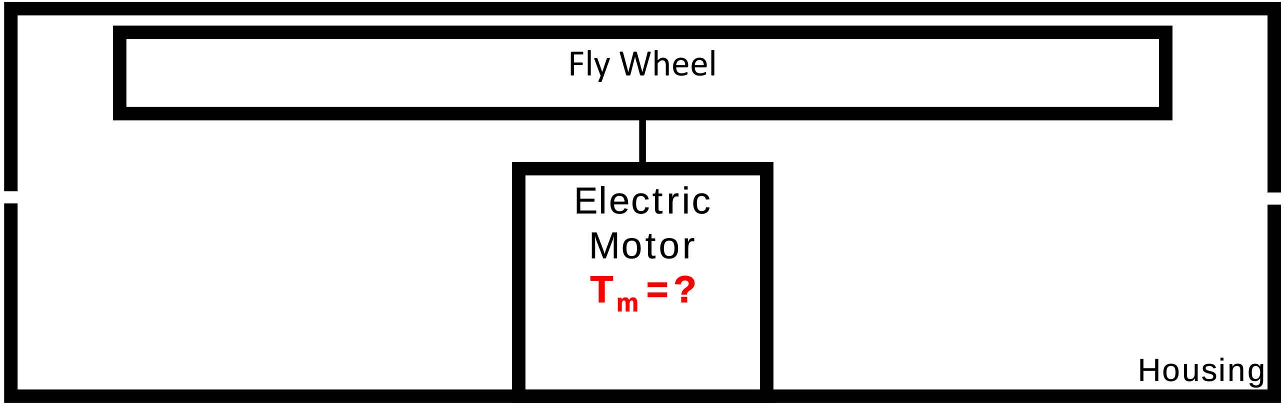
$T_{reaction}$ = 0.10 Nm from customer spec

$T_{friction}$ = 0.01 Nm from data sheet

$T_{magnetic}$ = 0.01 Nm from analysis

$T_{Windage}$ = 0.02 Nm from experience

$$T_m = 2 \cdot \left(1.5 \cdot T_{friction} + 1.5 \cdot T_{magnetic} + 3 \cdot T_{windage}\right) + T_{reaction} = 0.295 Nm$$



Fly Wheel

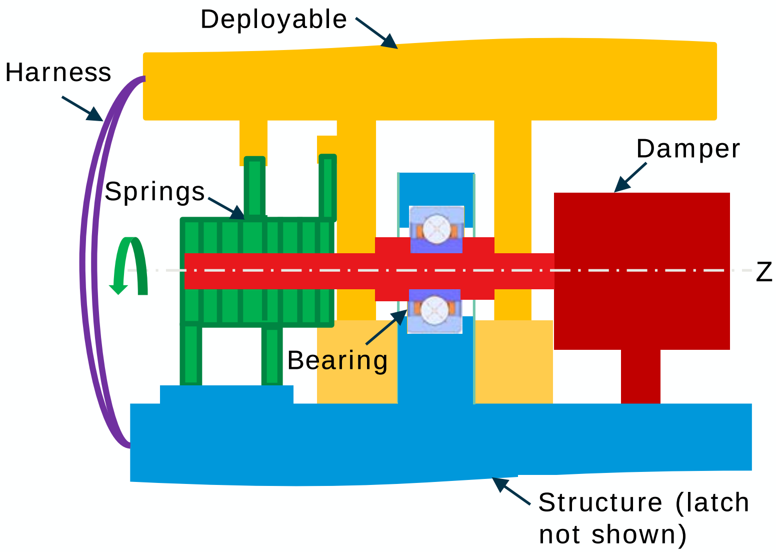
Electric Motor

$T_m = ?$

Housing

Exercise: Motorisation II

Spring driven deployment mechanism



<u>Relevant Requirements:</u>

R1. Deployment angle = 60 °

R2. Deployable CoG distance from Z = 1.5 m

R3. Deployable mass = 10 kg

R4. Max global acc = 0.1 m/s^2 (any axis)
(note: also be aware of any rotational accelerations)

The minimum actuation torque (T_{min}) shall be derived by the equation:

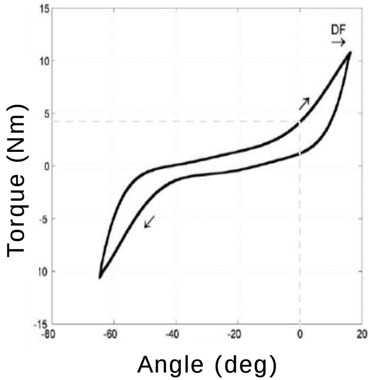
$$T_{\min} = 2 \times (1{,}1\, I + 1{,}2\cancel{S} + 1{,}5\, H_M + 3\, F_R + 3\, H_Y + 3\, H_A + 3\, H_D) + 1\cancel{{,}2}5\, T_D + \cancel{T_L}$$

Exercise: Motorisation II

Spring driven deployment mechanism

Example Budget:

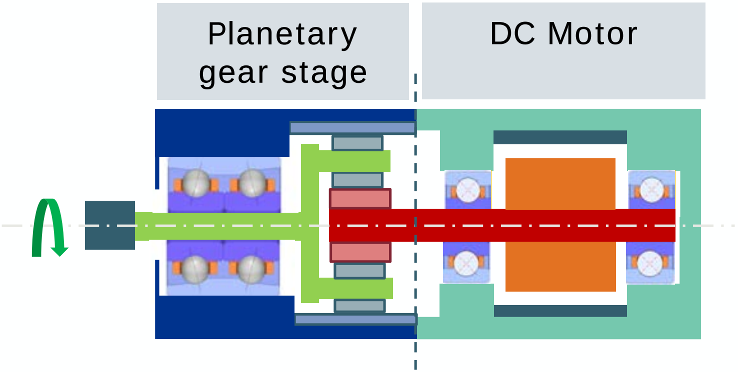
Contributor Description	**Contributor Origin**	**Values**	**Units**	**ECSS Factor**	**Factored Contribution**	**Reference**
Inertia	I	1.5	Nm	1.1	1.65	*Derived from requirements R2, R3 & R4.*
Bearing Friction	Friction (FR)	0.1	Nm	1.5	0.15	*Tested at bearing level. Report xxx.*
Damper	Friction (FR)	0.2	Nm	1.5	0.3	*Tested at damper level. Report xxx.*
Latch	Friction (FR)	0.1	Nm	3	0.3	*Predicted by analysis. Report xxx.*
Harness	Other (HA)	4	Nm	1.5	6	*Tested on Harness EM. Report xxx.*
	Magnetic effects	n/a	n/a	n/a	n/a	n/a
	Hysteresis	n/a	n/a	n/a	n/a	n/a
	Adhesion	n/a	n/a	n/a	n/a	n/a
	Dynamic Acceleration	n/a	n/a	n/a	n/a	n/a
Total Resistance		**5.9**	**Nm**		**8.4**	
Torque including motorisation factor				2	16.8	
Min required torque per spring	Spring		**Nm**	0.8	**21**	



e.g. Harness resistance data

Exercise: Motorisation III

DC motor with reduction stage



Example Relevant Requirements:

R1. Output Torque = 0.2 Nm

R2. Max commanded speed = 1.5 rads/s

R3. Max command current = 2 A

R4. Max command voltage = 24 V

R5. Temperature range = -20 °C to 30 °C

$$T_{\min} = 2\times(1{,}1\,I + 1{,}2\,S + 1{,}5\,H_M + 3\,F_R + 3\,H_Y + 3\,H_A + 3\,H_D) + 1{,}2\cancel{5}\,T_D + T_L$$

Exercise: Motorisation III

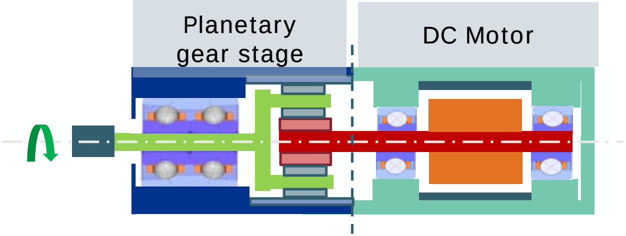
DC motor with reduction stage

Budget for cold case @ -20 °C Gear ratio : 8

Contributor Description	Contributor Origin	Units	Unfactored value at output	ECSS Uncertainty Factors	Factored Contribution @ Output	Factored Contribution @ Motor	Reference
Deliverable Output Torque	(T_L)	Nm	0.20	1.0	0.20	0.025	*Derived from requirement R1*
Gearbox output bearings	Friction (FR)	Nm	0.080	1.5	0.12	0.015	*Tested at bearing level. Report xxx.*
Planetary gear stage 1 (based on efficiency)	Friction (FR)	Nm	0.040	1.5	0.06	0.0075	*Tested at gear level. Report xxx.*
Motor Bearings Uncertainty	Friction (FR)	Nm	-	1.5-1=0.5	0.04	0.005	*Tested at bearing level. Report xxx.*
Total Resistance		Nm	0.200		0.22	0.028	
Motorisation factor			2		2	2	
Total incl. Motorisation factor		Nm	0.400		0.44	0.055	
Gearbox inertia	Inertial resistance (Td)	Nm	2.458E-04	1.25	3.07E-04	3.84E-05	*Actuator design report xxx.*
Min required torque	**0.055**	**Nm**					

This is a “black box” motor case needing caution

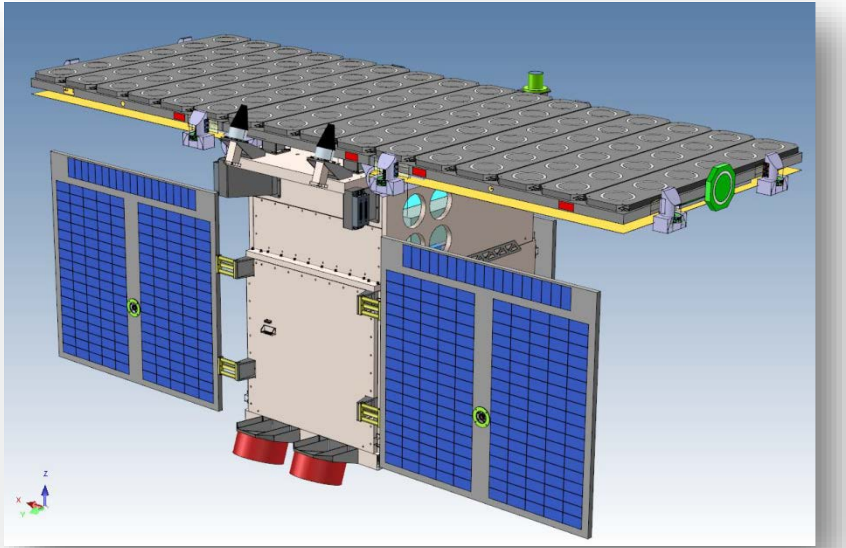
The budget is calculated from output to input to ensure the consequence of output uncertainty is reflected on gears



Design Requirements: end stops

For mechanisms with restricted travel or rotation:

- → Use of regular or emergency mechanical end stops (i.e. don’t rely on actuator function, e.g. by electric motor)
- → deployment indicators shall not be used as mechanical end stops
- → Requirements on separable contact surfaces do apply (see next slide)



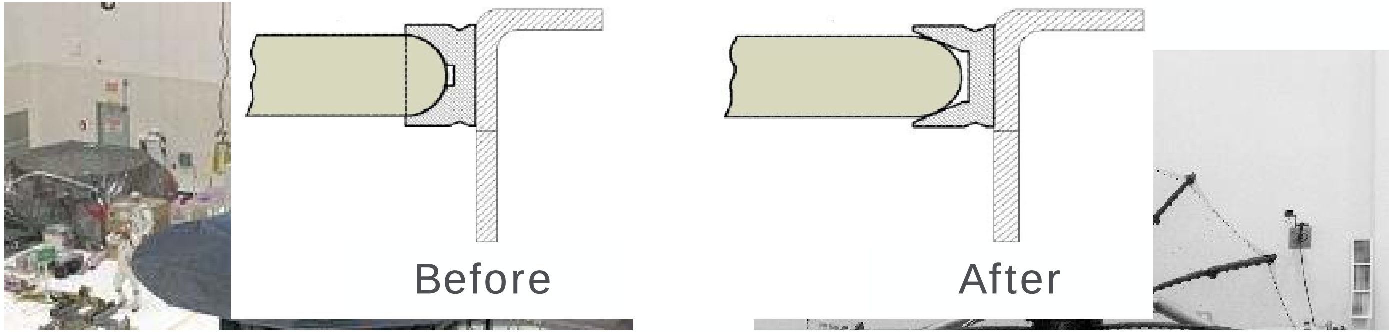
Courtesy of Qinetiq Space N.V.

Design Requirements: separable contact surfaces

(other than gears, balls and journal bearings)

- maintain **adhesion forces** below the specified limits
- contact between the mating surfaces **shall be characterized**
  - → surface roughness, hardness, contact geometry
- the **peak hertzian contact stress** shall be verified to be below 93 % of the yield limit of the weakest material
- avoid potential contact surface **property changes**
- for metallic surfaces (→ risk of **cold welding**!):
  - → minimum **hardness** of 500HV
  - → use of **dissimilar metal** (conflict with galvanic corrosion constraints)
  - → use of lubricant / dissimilar coatings

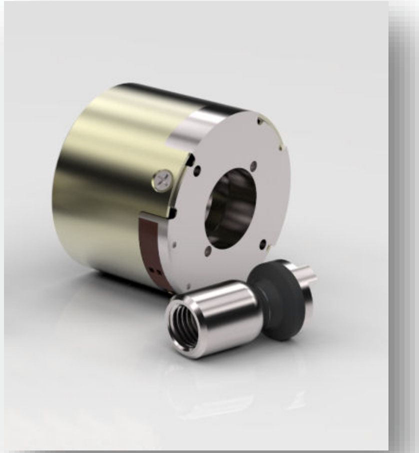
Example: NASA’s Galileo High Gain Antenna



- → Introduction of a “minor” design change
- → Significant increase in hertzian contact pressure (in particular during launch vibrations)
- → Lubrication breakdown
- → Relative motion in vacuum leading to cold welding between pin and socket
- → Partial deployment failure
- → Significantly reduced down-link rate

Design Requirements: Threaded parts

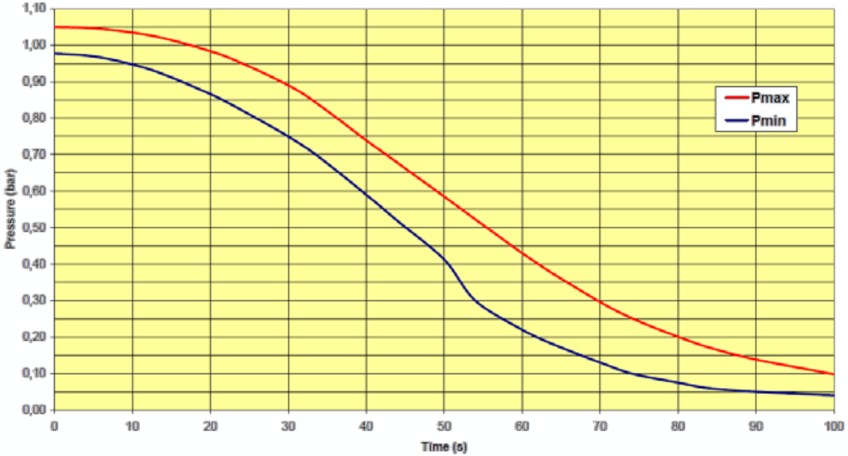
- Use of materials not susceptible to **stress corrosion cracking**
  - → Material selection according to ECSS-Q-ST-70-36C
- shall be designed to be **fail-safe** **≠ safe life**
  - → **Fracture control** requirements in ECSS-E-ST-32-01C Rev.1
- **preload** shall be justified taking into account **scattering** of all parameters
  - → e.g. manufacturing, lubrication and tightening tolerances



http://www.neaelectronics.com/

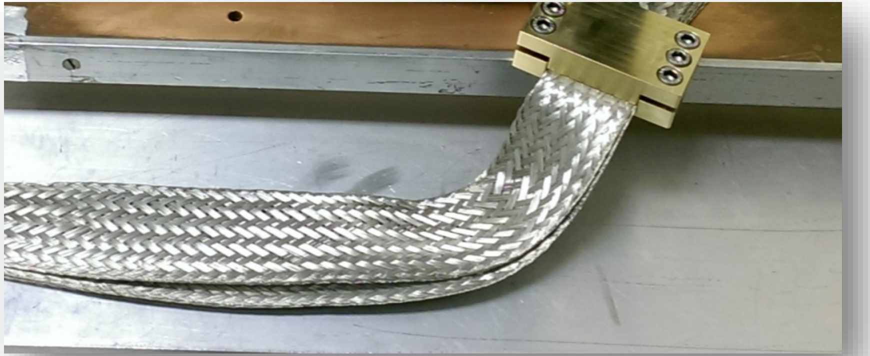
Design Requirements: Venting

- all closed cavities shall be provided with a **venting hole**
- **prevent particles contamination** of bearings, optics and external sensitive components
  - → e.g. by means of filters
- **compatibility of the lubricant** with the other spacecraft materials



Design Requirements: Grounding

- Each mechanism shall be **electrically bonded** to the spacecraft structure
- a ground **bonding strap** shall be used between the mechanism housing and the mounting ground plane
- the **length-to-width ratio** of the bonding strap should be smaller than four
- **DC resistance** shall be less than 10 mΩ.



Design Requirements: Others

Other design requirements, regarding:

- Open and closed loop **control systems** (e.g. gain and phase margins)
- Electrical **insulation**
- **Strain** on wires
- Mechanical **clearances** (e.g. MLI support locations)
- Marking and **labelling**
- Flushing and **purging**
- Thermal control (shall be **passive**!)
- **Magnetic cleanliness / EMC**

Verification Requirements: General

Verification process in conformance with

ECSS-E-ST-10-02 (Verification)

Review of design, Inspection, Measurement, **Analysis**, **Test**

→ Verification matrix shall be established

Verification by analysis

… shall cover extreme conditions

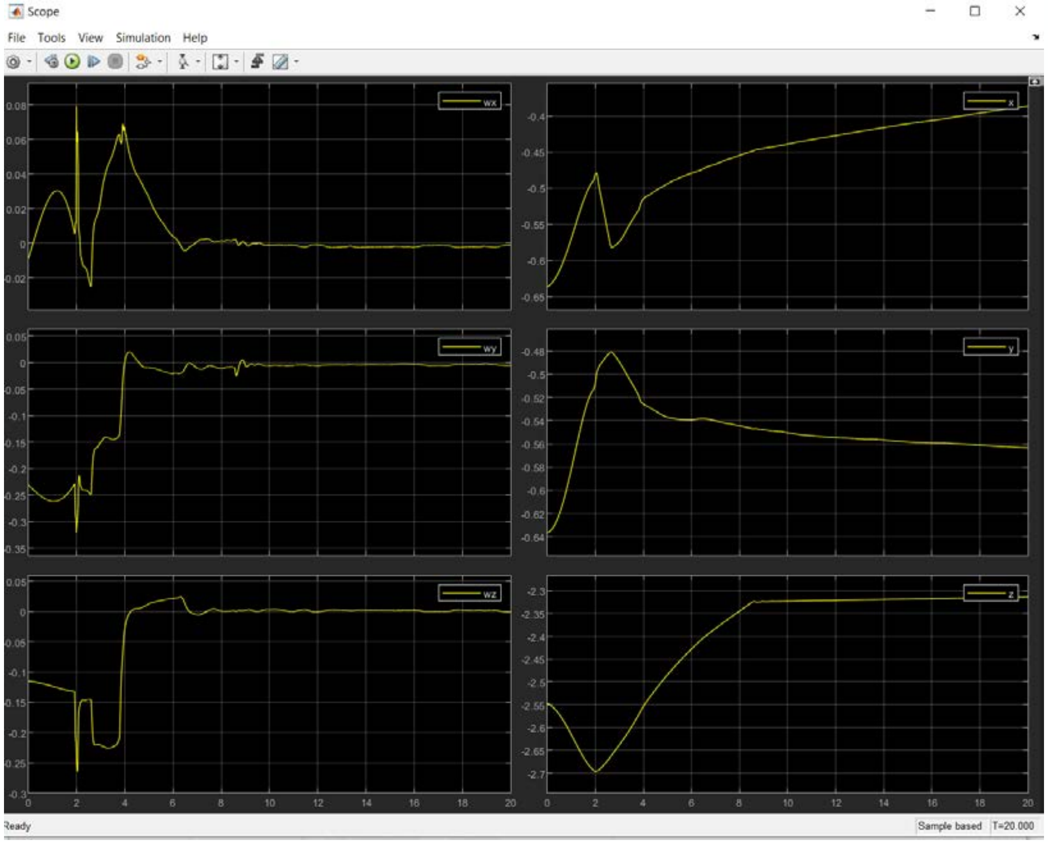
- — In flight
- — On ground

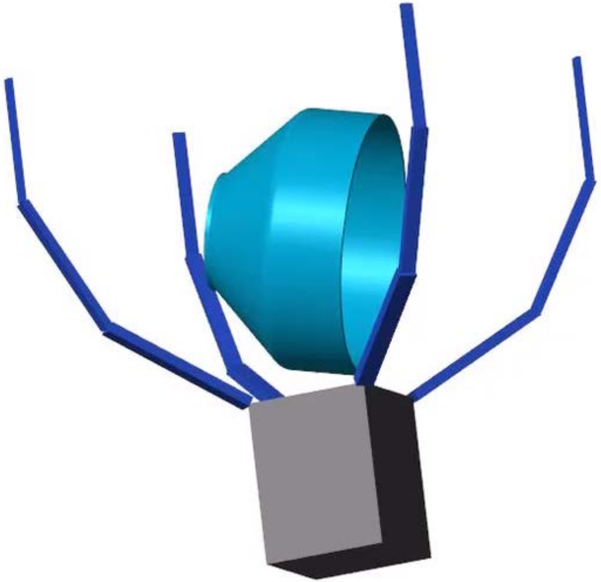
❑ Thermal analysis
❑ Structural analysis
❑ Preload budget
❑ Functional performance analysis
❑ Hertzian contact analysis
❑ Functional dimensioning analysis
❑ Reliability analysis, FMECA
❑ Gear analysis
❑ Shock generation and susceptibility
❑ Disturbance generation and susceptibility
❑ Analysis of control systems
❑ Lubrication analysis
❑ Lifetime analysis
❑ Hygroscopic effect analysis
❑ Magnetic and electromagnetic analysis
❑ Radiation analysis
❑ Electrical analysis

Functional performance analysis

- Analytical / numerical model based using, e.g.
  - MS Excel, hand calculation
  - Matlab / Simulink
  - Multi-body simulation tools: Simscape, MSC Adams, Dcap, …
  - Many more suitable tools
- Verify actuator design / sizing, performance, load generation, motion profile, etc.
- Sensitivity analysis, analyze failure cases
- For deployables / complex robotics systems: main verification technique
- always requires correlation with hardware test dat

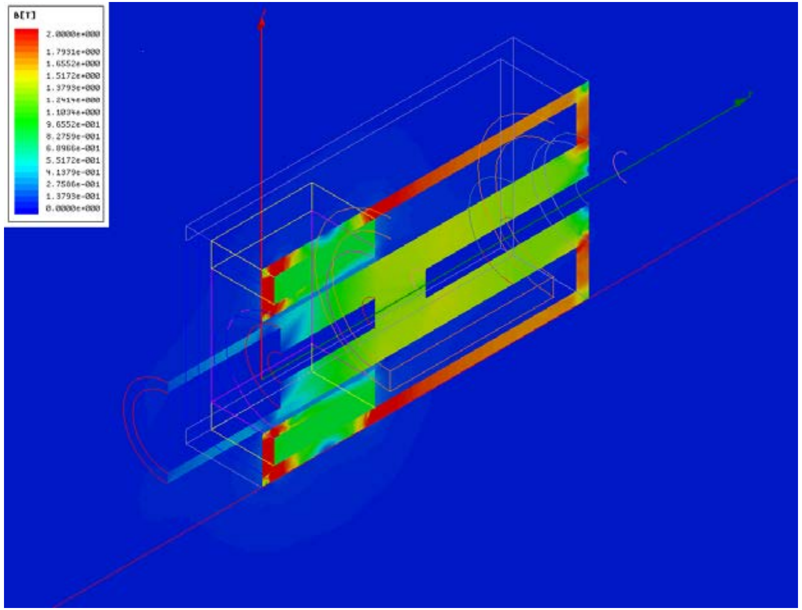
Functional performance analysis (example)

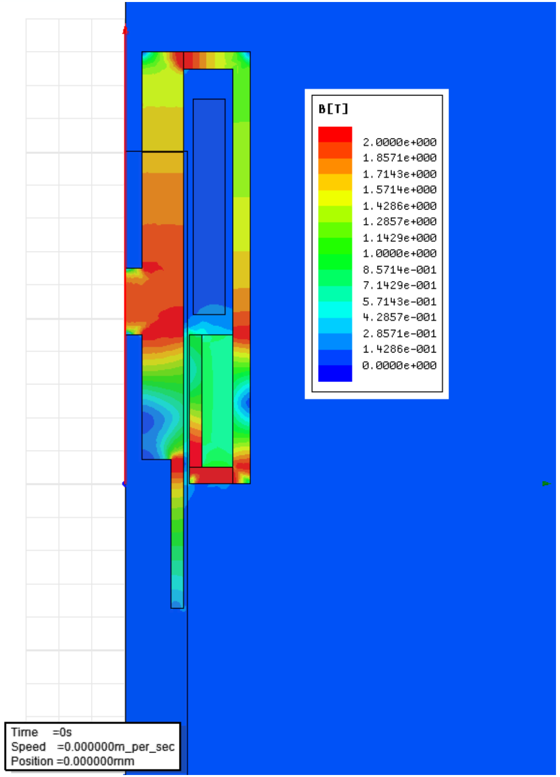




Magnetic and electromagnetic analysis

Example: Polarised Solenoid (Pin Puller)





Ball bearing analysis

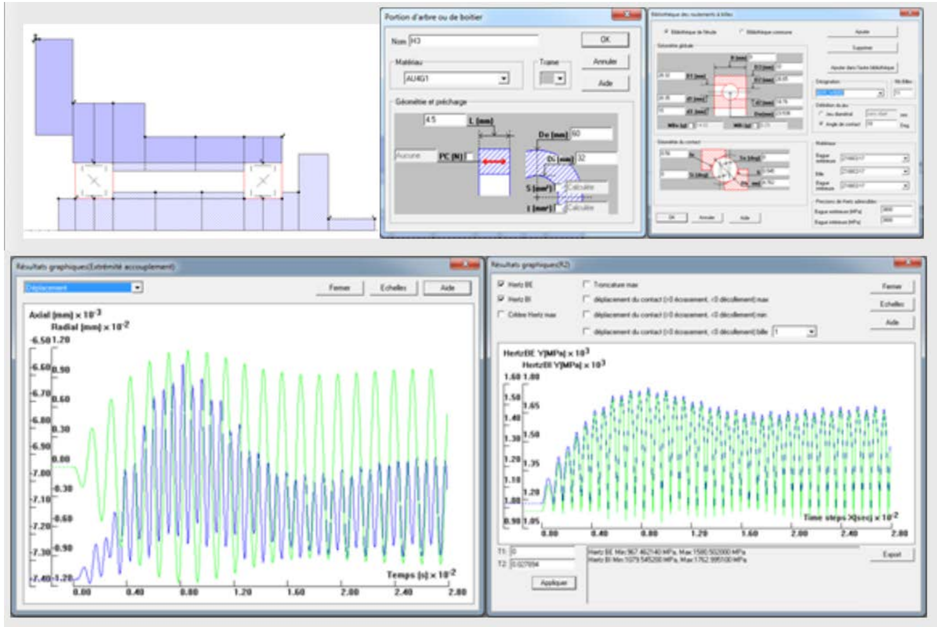
- Analysis of the **predicted hertzian contact stress** to verify the compliance with the material allowable

- Analysis to verify **sizing of ball bearings** in conformance with the allowable peak hertzian contact stress

  - → Ball bearing analysis tools: CABARET, RBSDyn, KISSsoft, ORBIN

  - → Also for separable contact surfaces, gears, end stops

RBSDYN by CNES



source: https://logiciels.cnes.fr/en/node/56?type=desc

Disturbance generation

Example: Microvibration generation of reaction wheels

- Bearing geometry
- Unbalance
- Structural resonances (e.g. FEM model)
- Control frequencies
- Rotor dynamics

$$\boxed{FTF = \frac{f_r}{2} \cdot \left(1 - \frac{d}{D} \cdot \cos\alpha\right)}$$

e.g. Fundamental train frequency

Lubrication analysis

Analysis of quantity of liquid lubrication based on

- partial / ambient pressure
- temperature
- design of labyrinth seal

$$\frac{dm}{dt} = (p_v - p_p)\sqrt{\frac{M}{2 \cdot \pi \cdot R \cdot T}}$$

e.g. Langmuir equation to analyse oil loss by evaporation

$$\frac{dm}{dt} = \frac{(p_i - p_o) \cdot d \cdot b \cdot v}{(4 + \frac{1.5}{b})}$$

e.g. mass flow over labyrinth seal according to Space Tribology Handbook (ESTL)

Potential Oil Loss Mechanisms:

Creep, centrifugal forces, evaporation, absorption by porous materials

Verification by test

- The tests to be performed shall be
  - Defined in a test plan
  - Agreed by the customer
- conformance to ECSS and mechanisms specification
- conformance to functional dimensioning
- performance in launch and operation configuration
- thermal verification
- structural verification
- characterize the dynamic behavior

- Characterisation testing
- Qualification testing
- Acceptance testing

Characterisation testing

- Breadboard model testing during **Phase A or B**

- Gain confidence in technology (no flight representative hardware)

  - Functional performance test
  - Vibration and thermal tests
  - Tribological lifetime test on critical items

    (Example: usage of certain lubricant in bearing / gear test rig)

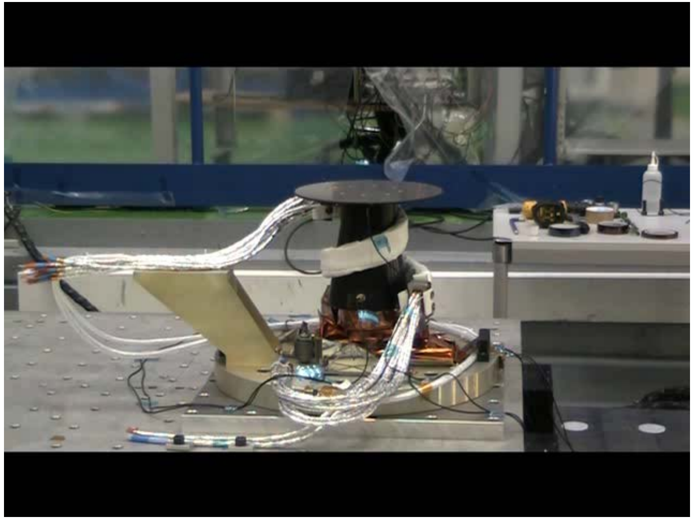
→ **No formal qualification!**

Qualification testing

All mechanisms shall be qualified for the application

Representative sequence and representative environment (test as you fly!)

→ Mandatory testing content in **ECSS-E-ST-10-03C (Testing), table 5-1**



Life test model

Flight representativeness regards:

- *Design (dimensions, tolerances, surface properties)*
- *Part quality*
- *Materials*
- *Processes*
- *Pre-conditioning (accept. test, run-in)*
- *Operation (e.g. speed profile, control, duration)*

→ The life test model shall be equal to the FM**, but shall not be the FM**

→ Best practice: **life qualification on the QM**

Lifetime related effects / failure modes

cycle dependent

Time dependent

- **Wear out**
- **Accumulation of wear**
- **Pitting**
- **Fretting**
- **Material fatigue**
- **Settling**
- **Defect propagation**
- **Lubricant deterioration**
  (e.g. oil separation, chemical reaction)
- **Oil loss**
  (e.g. migration, evaporation, absorption, diffusion)
- **Creep**

- **radiation effects**
- **thermal effects**
- **electromigration**
- **storage effects**

not addressed by ECSS-E-ST-33-01C

Pre-conditioning

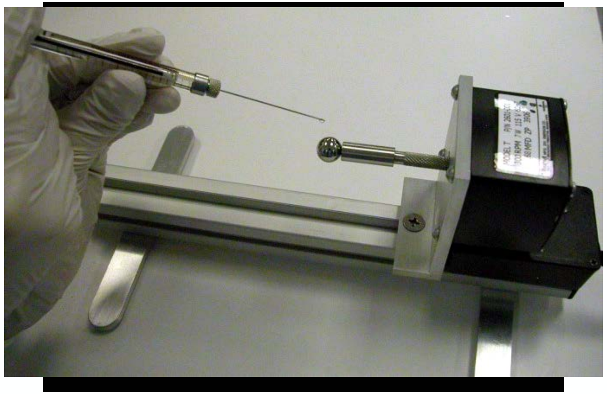
1. **Flight-representative assembly and integration**

   e.g. pre-loading, lubricant quantity and application process etc.

2. **Run-in and thermal settling (cycling)**

3. **Vibration testing**

   (ECSS-E-ST-33-01C, para. 4.8.3.3.11 b)



Courtesy of ESTL

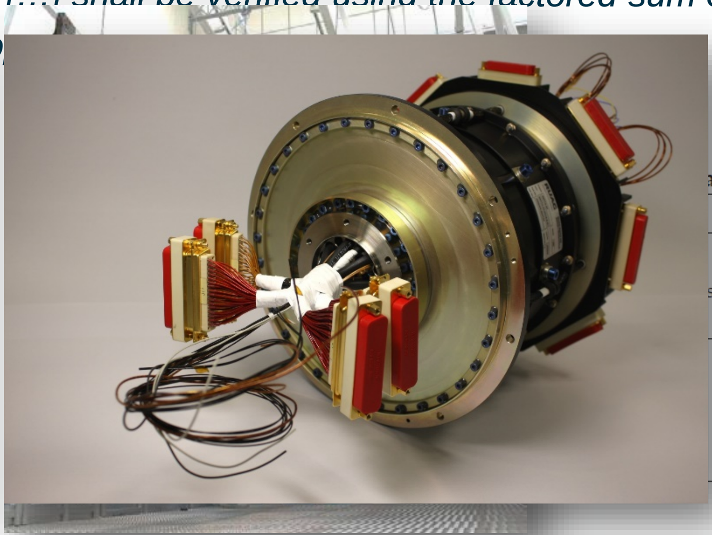
$$\boxed{1 \times qual.\,test + n \times (accept.)\; test}$$

Including sub-system and system level tests!

Life test duration

“ […] shall be verified using the factored sum of the predicted nominal ground test cycles […] and the in-orbit

o



able 4-4: Life test duration factors

	Number of expected cycles	Factor
	1 to 1 000 cycles	4
s to	1 001 to 100 000 cycles	2
	> 100 000 cycles	1,25
	1 to 10 cycles	10
	11 to 1 000 cycles	4
	1 001 to 100 000 cycles	2
	> 100 000 cycles	1,25

	e.g. SA deployment	e.g. SADM
No. of in-orbit cycles	1	29219
on-ground	2	320
lifetest	$1 \times 10 + 10 = 20$	$10 \cdot 10 + 990 \cdot 4 + 28219 \cdot 2 + 10 \cdot 10 + 320 \cdot 4 = 61878$

Accelerated life testing

- Acceleration: Increasing the rate of ageing by increasing st ctors
  by a known amount!

  - Example: compr
    (with long peri
    pointing, sc

Stress factors

temperature

contact stress

current density

temperature cycles

radiation

speed

voltage

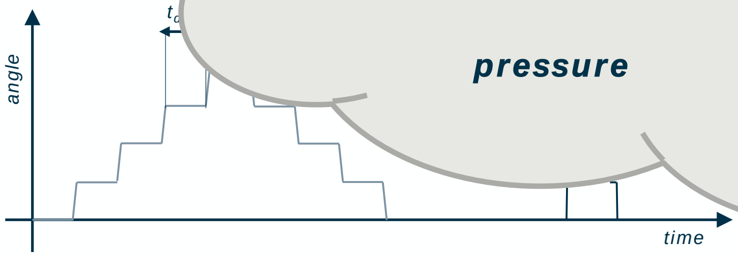
pressure

operational frequency

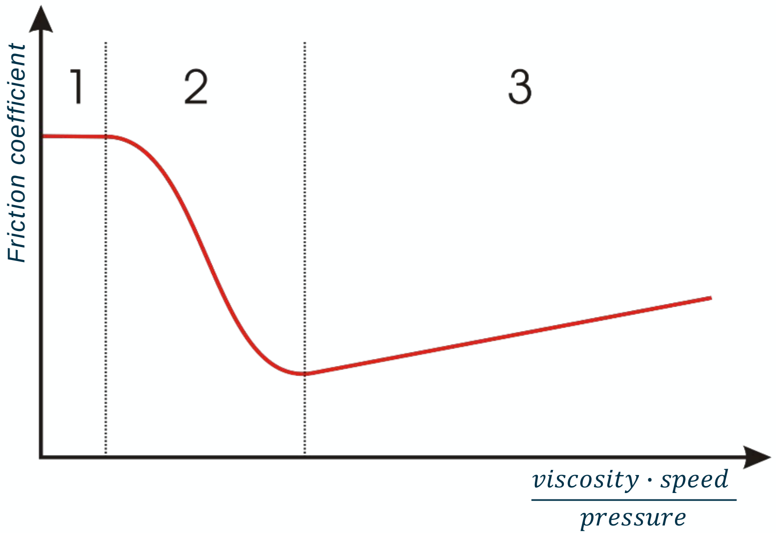
tional level

effects & e modes are the same

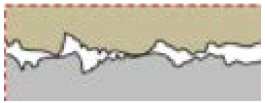
nominal operational level



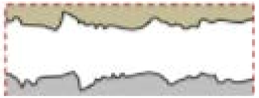
Stribeck – introduction into lubrication regimes



boundary lubrication
continuous asperity contact
high friction and wear rate



mixed lubrication
some asperity contact
fluid film carries load



hydrodynamic lubrication
no metal-to-metal contact
viscous friction

Stribeck cont'd

The λ-ra

With

λ >10 :

10> λ ≥3:

0.8< λ <3

λ ≤0.8:

From [9] for elliptical contacts:

$$U = \eta_0 * \frac{v}{E'R_x}$$

$$G = E\alpha$$

$$W = \frac{F}{E'R_x^2}$$

$$k = \frac{a}{b} (ellipticity\ parameter)$$

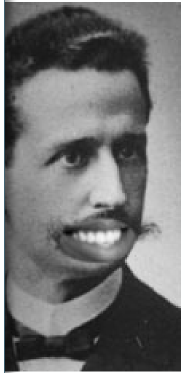
$$\eta_0 = Base\ viscosity\ of\ lubricant$$

$$E' = reduced\ elatsic\ modulus$$

$$F = elliptic\ integral\ (= 1.5277 + 0.60.23 \ln(R_x/R_y))$$

$$\alpha = Lubricant\ pressure - viscosity\ coefficient$$

$$a, b = Hertzian\ contact\ semi - mino\ and\ semi - major\ dimensions$$



Conclusion on accelerated life testing

- **General**
  - *Life test as much as possible flight representative*
  - *Every deviation from flight condition to be carefully assessed*

- **Accelerated testing**
  - *Numerous ageing effects and failure modes*
  - *Stress factors contribute differently*
  - *Ageing effects shall remain representative*
  - *Acceleration by increased*
    - *Frequency of operation: OK (unless very long standstill)*
    - *Temperature: NOK*
    - *Speed: OK for fluid and dry lube; NOK for greases*
    - *Other stress factors: check case-by-case*

Qualification testing success criteria

Disassembly and visual inspection of tribological parts:

- No direct contact between metallic parts
- Surface properties of contact surfaces not modified beyond specified limits
- No chemical deterioration beyond the specified limits of fluid lubricants
- Amount and size of wear acceptable (performance, contamination)
- Resistive torques according to 4.7.5.3. (motorization)
- Less than 50% degradation of resistive torques / forces
- Performance according to spec

Acceptance testing

- Tests to confirm that flight hardware free from manufacturing defects;
- Test content according to ECSS-E-ST-10-03C, table 5-3;
- Vibration levels and thermal loads which are higher than expected in flight but less than qualification
- Refurbishment should not be performed after successful acceptance testing

Thank you for your attention!