DEVELOPMENT OF THE LID OPENING MECHANISM (LOM)

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ABSTRACT

The Lid Opening Mechanism (LOM) is part of the enclosure for the Field Emission Electric Propulsion (FEEP) Thruster Assembly. It hermetically seals the inner parts of the volume which contains caesium. The inner volume is purged with argon to protect the caesium against ambient air and water.
The LOM must be able to maintain the overpressure for 3 years of ground activities and during launch into space. The Lid is opened on telemetry command during satellite commissioning. Once opened in space, it remains open.
Oerlikon Space AG (formerly Contraves Space AG) was awarded by ESA a contract to develop and qualify the LOM and to deliver 3 EM's and 15 FM's to ALTA who will integrate them onto their Thruster Unit.
This paper describes the development logic, the design evolution and trade-offs which were performed during the design phase, as well as problems encountered and solved during testing.

1. INTRODUCTION

Field Emission Electric Propulsion (FEEP) Thrusters are particularly suitable for missions requiring thrusts in the sub-millinewton level with precise control abilities. FEEPs feature unmatched performance at the 1 µN - 1 mN thrust level, and is unique for some highly demanding applications like drag-free control of scientific spacecraft and disturbance reduction of microgravity platforms. FEEP will be used on space missions as Microscope or LISA.

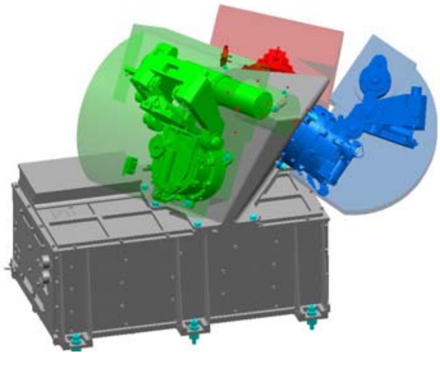

Figure 1: EPSA with 3 TA's for Microscope (test configuration with GSE on LOM)

The Lid Opening Mechanism (LOM) is part of the Thruster Assembly (TA), which again is part of the Electric Propulsion Subsystem Assembly (EPSA). The Thruster Assembly is a propulsion device based on the Field Emission Electric Propulsion (FEEP) technology. It is composed of the following elements:

- Thruster Unit (TU), to generate thrust. It is based on high voltage parts (some charged up to 9 kV and others to -4 kV), producing ionisation and acceleration of the caesium ions.
- Propellant tank, providing the caesium propellant feeding the TU.
- Lid Opening Mechanism (LOM): Container body with Lid and Lid Opening Mechanism.

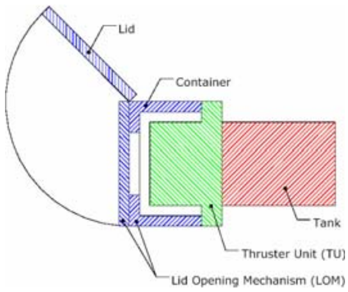

Figure 2: FEEP Thruster Assembly

The main function of the LOM is to protect the Caesium, contained in the TU, from reaction with ambient air and water. Mated to the Thruster Unit in a vacuum chamber the container then is pressurized with argon at 1.5 bar. The LOM remains closed during ground operations and during launch. An overpressure against the environment must be maintained over a period of 3 years. This time includes storage, integration onto the spacecraft, followed by system tests and transport of the spacecraft and finally the launch into space.
The Lid is opened on telemetry command during satellite commissioning. Once opened in space, it remains open. For ground firing testing of the TU in a vacuum chamber the LOM is equipped with a Closing Ground Support Equipment (CGSE) which gives the possibility to close the Lid in the vacuum chamber. This is necessary to remove the unit from the chamber, to run further tests and as an emergency closing provision in case of vacuum loss during testing.

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2. REQUIREMENTS

2.1. Main Requirements

The maximal container absolute pressure of argon shall be 1.5 bar at 20°C. The LOM leak rate in the overpressure condition shall be such that at least 50 mbar residual overpressure with respect to ambient pressure are maintained throughout the specified ground lifetime, in the specified ground storage thermal conditions. (For the specified 3 years lifetime and 1.5 bar)

The LOM must be re-closable for testing in the vacuum chamber. A GSE must be provided that does the closing in the chamber. The LOM must be designed for 10 opening/closing cycles on ground plus 1 opening in space.

A pressure sensor is part of the LOM which provides control of the inner pressure during all ground activities.

The total mass of the LOM shall be lower than 320 g including harness.

Stiffness requirement are 350 Hz for the Launch configuration and 70 Hz for the in-orbit configuration with the Lid in the open position. The vibration and shock requirements correspond to quasi static loads of 120g in any direction.

The thermal requirements are as follows:

A Bake out process must be done prior to delivery. This process consists of heating the closed LOM to 150°C while connected to a vacuum pump for minimum 5 days. For that process the Wax Actuator must be removed as its upper temperature limit is +80°C.

The non operating temperature before Lid opening ranges from -60°C to +80°C. The temperature during Lid opening is between -30°C to +80°C. After Lid opening the LOM temperature is between -60°C and +110°C.

2.2. Design Restrictions

The Actuator element was defined by ESA: The lid unlatching actuator shall be a paraffin actuator Starsys type EH-3525 or equivalent. This actuator delivers a minimum nominal force of 156 N over a stroke of 6.5mm. The Actuator must be placed on top of the Lid due to volume constraints around the Unit.

The LOM shall be resettable using a specific MGSE.

The LOM internal pressure monitoring shall be provided whenever the lid is closed.

3. MAIN DESIGN DRIVERS

From the requirements above the following main design drivers were identified:

- Sealing of the unit with an internal overpressure of 0.5 bar during storage and 1.5 bar during tests and during launch. This requires a sealing system which fulfils the leak requirement and which keeps the Lid tightly closed under vibration and thermal cycling. The operational temperature is -30°C to +80°C. A bake-out at 150°C must also be taken in account.
- Releasing the Lid from the closed position using a Wax Actuator. Optimising the design in order to make best use of the Actuator performance.
- The stored energy of the overpressure is taken into account when the Lid is released.
- Ensure that the Lid opens even without inner pressure at worst case temperature conditions.
- For the rotation of the Lid to the open position, sufficient motorization margin must be provided and the shock at the end stop must be minimized.

4. SEALING

The LOM has 3 interfaces which have to be sealed: one static Interface to the TU, one static interface for the pressure sensor, one separable interface between the LOM Housing and the Lid. The last one is considered as the most critical as it not only has to provide leak tightness but also separation of 2 interfaces.

Metallic seals provide very good leak tightness and can be used over a wide temperature range. On the negative side is the fact that a very high preload is needed to deform them plus that they cannot be used for 10 opening / closing cycles without degradation of the sealing performance.

O-Rings can be used for many closing cycles and need relatively low pressure to provide the sealing. On the negative side are their higher gas permeability and the restriction in temperature limits.

Based on in-house experience with static seals tested down to -130°C and from material data of possible materials Viton (FPM) was found to be the best solution wrt leak tightness and temperature limits.

5. RELEASE MECHANISM TRADE OFF

5.1. Design Principles

To make the best use of the given linear wax actuator different design solutions were investigated. The following requirements had to be fulfilled:

The wax actuator must be placed on top of the Lid due to the volume constraints from higher level.

The Lid must open with an inside pressure of 1.8 bar and vacuum outside as well as with vacuum inside and outside. These are the 2 extreme cases. The first case assumes launch with 1.5 bar inner pressure and opening in space at 80°C. The second case corresponds to complete pressure loss during launch, i.e. sealing is lost, inner pressure is equal to outer pressure.

In the closed condition the force to deform the O-Ring must also be taken into account.
The requirement for ground testing calls for a re-closing with a GSE. It was therefore desirable to design a latch system which locks itself when the Lid is rotated back from the open position to the closed position using the GSE.
Following 3 typical concepts which were investigated.

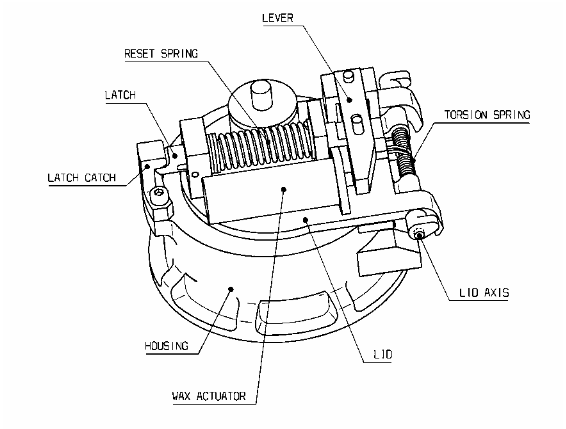


Figure 3: V11 - Linear Latch plus Lever System

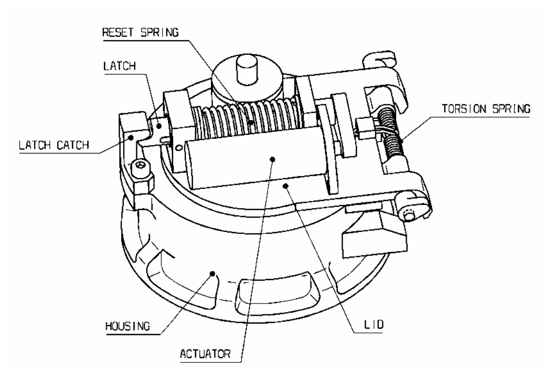


Figure 4: V12 - Linear Latch with Direct Actuation

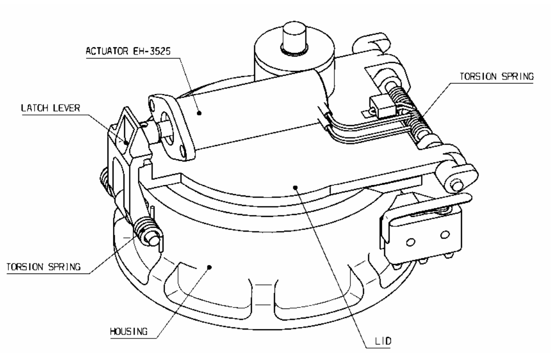


Figure 5: V15 - Rotary Latch

The finding was that the parasitic friction forces for V15 with the Rotary Latch are much smaller than for V11 and V12 which use a linear Latch. V15 was chosen as design baseline.

5.2. Overpressure release

A rough estimation of the stored energy of 1.5 bar (assuming 100% efficiency and 0.125 kg for the Lid unit) lead to the following result: The stored energy of 1.5 bar inside the LOM with a volume of 6.5E4 mm3 is equal to a kinetic energy of 12.6 m/s (45 km/h). This was judged to be very critical as it will result in a considerable shock at the end stop. Derived from that was a requirement that the overpressure shall be released before the Lid is completely free to rotate, i.e. that an opening in 2 steps is mandatory.
The principle of the 2 step opening is as follows:
The wax actuator provides a constant movement of the actuator rod which results in a constant rotation of the Latch. If the Latch is equipped with an additional step, an intermediate stop of the Lid can be provided. The opening sequence is then as follows:

- High force stroke against friction force from O-Ring and overpressure
- Jump to a first stop at 1.5°→ gap between Lid and seal → release overpressure
- Complete release of Lid to rotate to open position / end stop

5.3. Release mechanism refinement

Further refinement of V15 and the need for overpressure release led to the final design with the Roller and the 2 steps on the Latch. The Roller further decreases the parasitic friction forces.

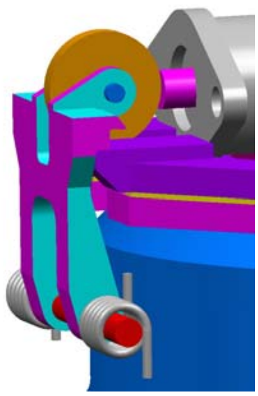


Figure 6: Latch with 2 Steps plus Roller

6. FULL OPENING, END STOP AND END SWITCHESS

After the initial release the Lid has to be moved to its end position. To be outside the plume of the Truster the Lid has to be rotated by 105°. The motorization is provided by 2 helical springs which sit on the Lid axis. The End Stop consists of a GFRP Spring Blade which also carries the End Switches which provide a redundant signal for the Lid open position.
The rotating Lid carries the Wax Actuator which is powered by 2 heater lines for redundancy. The heater cables are guided in Cable Drums in order to stay in place during vibration and move in a clear defined way during opening and re-closing of the Lid in the test chamber.

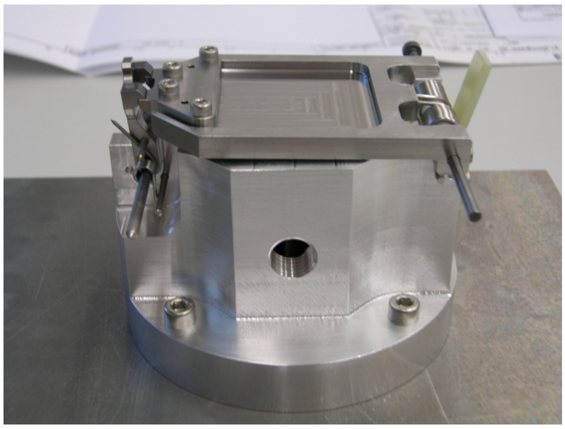


Figure 7: Bread Board Model (BBM)

7. BBM (BREAD BOARD MODEL)

While Eigenfrequencies, strength and other topics can be analyzed very precisely by FE modelling other behaviours are trickier to analyze. Especially dynamic behaviour in combination with friction, damping and manufacturing influences are difficult to simulate. It was therefore decided to build an in-house Bread-Board-Model (BBM).
With this model the following could be intensively tested:
Function of the 2 step opening of the Lid with pressure release. The tests showed that with increasing inner pressure and increased rounding of the edge between the first and second step there is a point were the Lid opens without stopping at the second step, i.e. the Lid is able to kick the Latch so far out, that the second step is out of reach.
With the nominal geometry the system worked perfectly, i.e. the Lid stopped at the 2nd step, the gas is released and then the opening is done by the helical springs only. This tests were done with overpressure of up to 3 bar.
The End Stop was also tested, showing that the damping of the Blade and the friction provide a good stop without having the Lid swinging back almost to its closed position.
Overall the BBM provided very good results and gave big confidence in the principle of the design.

Beside all the positive points, the BBM showed an effect which was not considered before: After exposing the Unit to high temperatures (150°C for several hours) the Lid was sticking to the O-Ring and would not open under the small opening force provided by the Lid springs.

8. O-RING STICKING

It was realized that the problem of O-Ring sticking could be the showstopper for the correct function of the LOM.
A program was initiated to test different O-Rings and material combinations. The tests were done using simple flanges onto which different surface treatments could be applied. Also different o-ring materials as well as different O-Ring coatings were tested. The tests were done by heating the test unit to 150°C (out-baking) followed by separation tests at room temperature and in a cold chamber at -18°C. The conclusions of intensive test were as follows:
Only Silicone O-Rings provide low enough sticking force to have a safe separation with the current design. As the permeability of silicone O-Rings is 200x to 400x higher than for Viton O-Rings the sealing requirement can not be fulfilled.
The best possible result was, that a sticking force of <10N is feasible when using specially out-baked Viton O-Rings. As this sticking force can not be separated by the Lid springs an additional force is needed for a safe separation.

9. DESIGN UPDATE (LIFTER AND SEAL)

Different designs were investigated how to separate the Lid from the O-Ring assuming a sticking force of 10N plus the needed margins for friction and motorization.

9.1. Use of inner pressure (V1)

Using the inner pressure looks at first sight to be a very attractive solution. It also means that no additional change to the hardware is needed. However 2 things present a severe drawback to this solution: The inner pressure must be high enough to separate the O-Ring from the Lid, i.e. it must be guaranteed that no degradation due to launch vibration occurres and that the extreme non-operating temperatures do not influence the leak rate. In addition even with the nominal leak rate the Lid must be opened within 3 month in orbit. This all guarantees opening of the Lid to the second step, i.e. an opening to 1.5°. At the second opening step (1.5°) the pressure drops to zero, but a small part of the O-ring is still in contact with the Lid. The sticking must be now low enough that it can be overcome with the torque of the Lid Springs doing the "peel off separation". All in all this version was considered as too risky.

9.2. Kick Off Springs (V2 & V3)

2 versions were investigated in which additional Kick-Off springs are placed between Housing and Lid. The position of the springs can be outside or inside, but the principle system is the same.
The springs can be designed that the force and length of the stroke is sufficient to open the Lid wide enough that no contact remains before the small motorization of the Lid springs takes over. There is also no restriction concerning time in orbit and leak rate in orbit, as the inner pressure is not needed. On the negative side there is an additional parasitic force wrt to the initial opening with the wax actuator, i.e. the friction forces become higher with increasing force from the Kick-Off Springs. As the motorization margin for the first step is used by a big part already from the friction forces produced by the O-Ring and the inner pressure the additional force from the springs is limited.

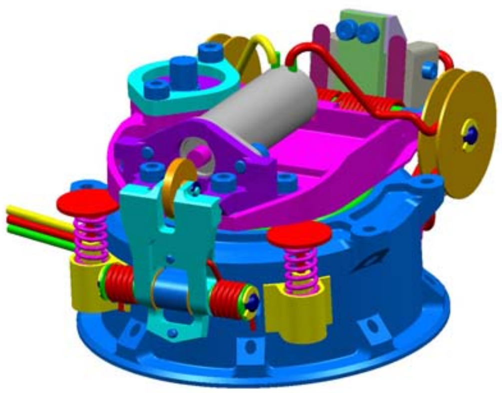


Figure 8: V2 – Kick off Springs outside

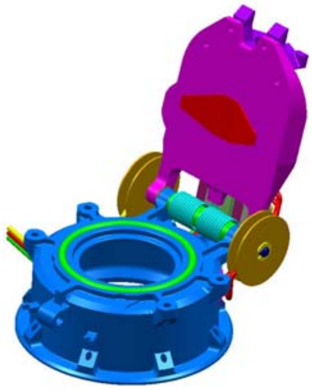


Figure 9: V3 – Kick off Springs inside

9.3. Lifter (V4)

This design is based on the idea to use the force of the wax actuator to provide the needed separation force. An additional element, called Lifter, is mounted to the Latch. It rotates with the Latch which is driven from the Wax Actuator. If no sticking occurs, the Lifter never gets in contact with the Lid. If sticking occurs, then the Lifter (driven by the Wax Actuator) pushes the Lid open. The big advantage is that the added Lifter has no influence on the system during first step separation; the wax actuator is used as planned. For the separation of the Lid from the O-Ring the full force of the wax actuator can be used for the Lifter.
There is also no restriction concerning time in orbit and leak rate in orbit, as the inner pressure is not needed.

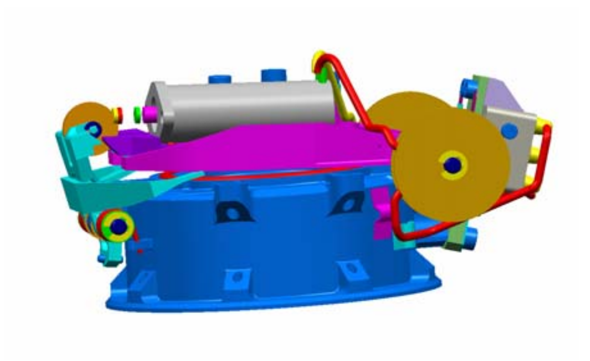
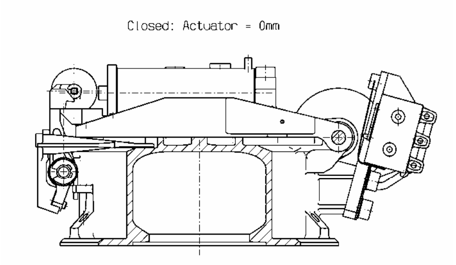


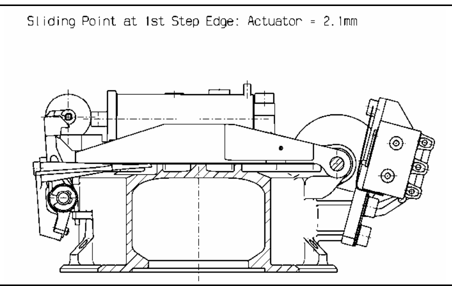
Figure 10: V4 - Lifter

9.4. Trade Off results

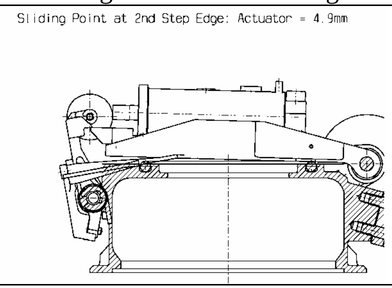
A Trade-Off was done taking into account even more points than mentioned above. The result was that the best technical solution is Version V-4 “Lifter” followed by Version V-2 “Outer Kick Off Springs”.
The design V-4 was chosen and optimized wrt to a maximum opening angle from the Lifter. It was built, installed in one of the EM’s and tested. It performed as planned. With the Lid sticking to the O-Ring (after 2 days at 150°C) the Lifter opened the Lid.



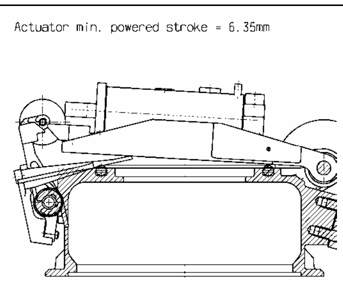
no contact of Lifter



if sticking: Lifter starts moving Lid



Lifter bends



end of min. powered stroke @ 3.35°Lid opening

Figure 11: Opening sequence with Lifter

9.5. Problems at cold

Surprisingly, further problems were encountered by vacuum tests at low temperature (-40°C). The combination of adhesion of the O-Ring to the Lid at 150°C and then going to -40°C proved to be a solid bond.
Whereas opening after the 150°C bake-out was possible at any temperature between 0°C and +80°C, the bonding forces at low temperature became too high to have an opening with the force provided by the wax actuator (and the strength of the Lifter).
Many tests were done to investigate that phenomena and it could be concluded that next to the bonding effect of the 150°C bake out, the hardening of the O-Ring at low temperatures is the cause. With the E-Modulus increasing dramatically below the TR10 point the O-Ring is so stiff, that it acts like a solid part and not any longer provides the elasticity which is needed to be peeled off.
The solution found is another compound which has a lower TR10 point. Although the permeability is not as good as Viton, it is still good enough to fulfil the leakage requirement of the whole system.

10. TESTING

The qualification of the LOM includes the following: The vibration and shock tests were done without any problems. No pressure loss was detected. The opening of the Lid is done in a vacuum chamber at temperatures between +80°C and -40°C. In order to control the motorization margin a number of tests were performed with the wax actuator removed. The actuation was done manually by using a spring gauge outside the vacuum chamber, using a vacuum feed-through. With this setup the required forces could be measured which were needed for opening of the first step plus separation of the Lid from the O-Ring using the Lifter.

Figure 12: Test setup for motorization margin tests with Spring Gauge outside and LOM with CGSE inside the vacuum chamber

With the modification described above the required motorization margins are now fulfilled.
The tests will proceed with a thermal cycling tests and openings of the LOM at different temperatures. For all

these tests the CGSE (Closing Ground Support Equipment) is needed. Finally the LOM will be stored for 6 month in order to check the pressure drop over time.

11. LOM BASELINE DESIGN

The LOM is manufactured mainly from Titanium alloy for compatibility with the caesium and for mass reasons. Rotating and sliding parts are surface treated to reduce friction and prevent cold welding or fretting.
Wax Actuator, Pressure Sensor and Micro Switches are made from stainless steel. The Lid Springs and the Latch Springs are made from stainless spring steel.
The function principle of the LOM is described in the chapters above, the final design of the LOM is presented in the figures hereafter.

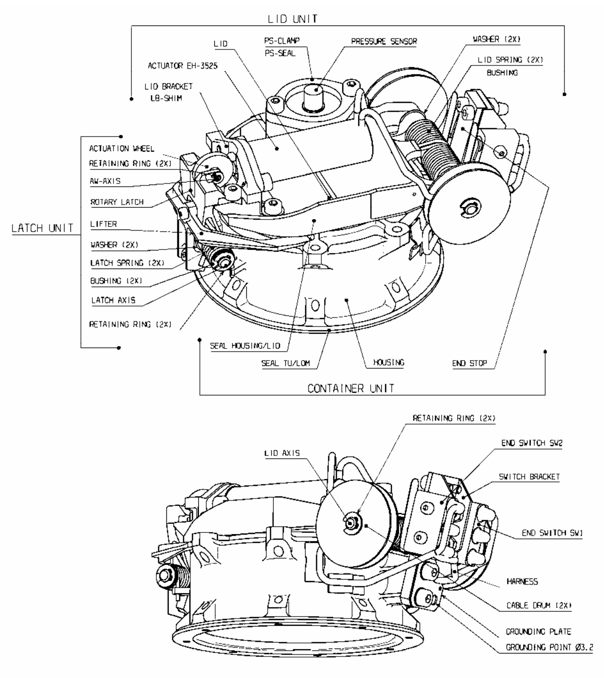


Figure 13: LOM Overview and designations

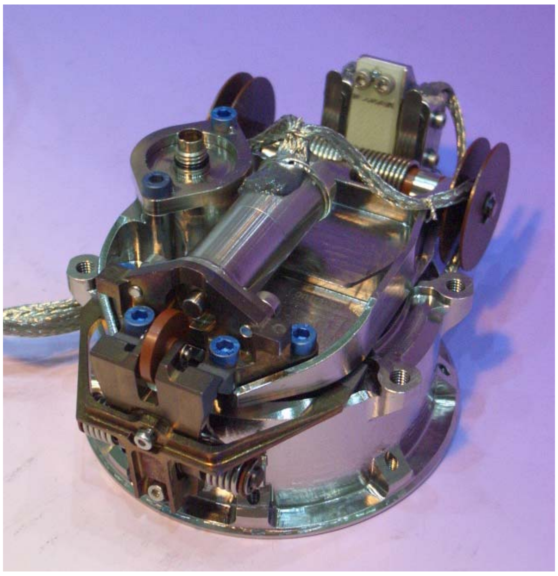


Figure 14: LOM in closed configuration (diameter 80mm, height 50mm)

Figure 15: LOM in open configuration

12. CGSE (CLOSING GROUND SUPPORT EQUIPMENT)

In parallel to the LOM itself a Closing Ground Support Equipment (CGSE) was also developed.
The CGSE consists of the mechanical unit which is mounted to the LOM in the vacuum chamber plus the drive electronics which is place outside the vacuum chamber.
The mechanical unit is based on a crank shaft drive and powered by a brushless electric motor. All parts are vacuum compatible. The crank shaft principle provides the required big forces at the very end of the closing cycle, when the force from the Latch spring has to be overcome and when the O-Ring has to be compressed.

The design is done in a way that no reversing of the system is needed. To minimize friction between the closing system and the Lid the CGSE is equipped with Rollers which contact the Lid. These Rollers are spring loaded so that a defined almost constant force is guaranteed at the end of the cycle.

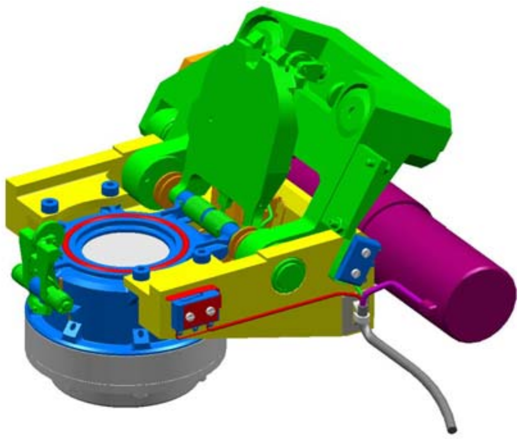


Figure 16: CGSE - Mechanical Unit Overview

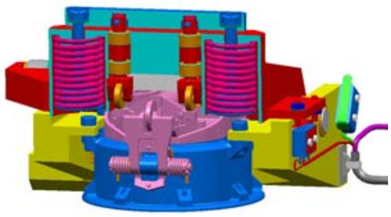


Figure 17: CGSE - Mechanical Unit with spring loaded Rollers for Lid contact

The drive electronics is able to control 3 LOM's with its CGSE, i.e. initiate the Wax Actuators of the LOM, read the signal of the End Switches and drive 3 Mechanical CGSE Units.

Figure 18: CGSE - Drive Electronics

13. CONCLUSIONS AND LESSONS LEARNED

The LOM is in the final steps of the qualification program. The development of the mechanism itself was successful and straightforward. Trade Offs for the different functions followed by discussions with the customer lead to an optimized design in a relatively short time. The early BBM proved to be very valuable to reduce risks.

The problems encountered with the sticking of the Lid to the O-Ring shows, that this point was underestimated from all parties involved. It was the only critical point which was treated on paper only (gas-permeability values, know-how from other projects for static application). After the first tests with real hardware the problem was discovered which led to an intensive investigation. It has to be noted that the problem in this form (+150°C bake-out and separation with low force between +80°C and -40°C) is not well known. O-Ring manufacturer, material and surface experts could not help successfully.

Concerning the overall system the following must be noted: The required architecture with the Wax Actuator and the Pressure Sensor on the rotating Lid is not the optimal solution. These elements add mass to the moving part and the Actuator needs cables which also have to rotate.

For future developments, some space might be allocated to accommodate the Actuator on the Housing if interface constraints should allow this.

14. ACKNOWLEDGEMENT

We would like to thank the FEEP thruster team at ALTA, especially Fabio Ceccanti and Mirko Spurio for the excellent goal oriented teamwork. Our thanks go also to ESA / ESTEC, Pierre Coste and Davide Nicolini for their valuable support.