DEMONSTRATION OF A NEW DUST RESILIENT THERMAL SHUTTER MECHANISM FOR LUNAR APPLICATIONS

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ABSTRACT

The ESA-funded Lunar Thermal Shutter (LTS) mechanism, developed by ESR Space and supported by Almatech and Spacemech, is a novel mechanism which provides a cover over radiators at or near the lunar surface. Consisting of a 710×410 mm frame, the LTS utilises a stepper-motor and arrangement of tensioned belts to draw an aluminised film over a radiator. The benefits of this system are two-fold: firstly, it protects the radiator from contamination with lunar regolith which can negatively impact thermal performance. Secondly, it allows the radiator area exposed to be varied, providing control of its effective emissivity. The mechanism is dust resilient and fully scalable, making it ideal for a wide range of future applications. These capabilities will extend system lifetimes through the maintenance of cleanliness and reliability, while enabling system level mass savings versus traditional radiators and lunar night survival by limiting dissipation of payloads such as for ESA Argonaut applications.

1 INTRODUCTION AND BACKGROUND

The LTS addresses the issues of lunar radiators being exposed to not only dust but also potentially a combination of high infrared loads and long lunar nights. This leads to the need to protect the radiator and vary its emissivity. This minimises the sizing of survival heater powers required in the coldest case and improves the cooling efficiency in the hot thermal case, ultimately allowing for a smaller radiator and the potential to reduce battery size.

At the start of project, both shutters and louvres were considered as potential design solutions and a concept for each was pursued in parallel prior to a trade-off. The result of this trade-off favoured the shutter due to its expected superior thermal performance, essentially because it allows the radiator to be fully exposed when needed. Any louvre concept would always provide some blocking of the radiator in the fully open case. The shutter approach was also noted to have fewer limiting cases with light trapping phenomena, though it was noted that the louvre held some advantages to limit the impact infrared (IR) and albedo heat fluxes, particularly at low-mid latitudes. However, with a declared bias toward polar applications, the shutter concept was selected.

1.1 Key Requirements

The objective of the shutter was to change the view factor of an underlying radiator to the external environment, be it space or the lunar surface. In addition to general good practice in space mechanism design, the design was required to be resilient to lunar regolith exposure. This meant that it was essential to preclude dust reaching sensitive tribological areas such as motor bearings.

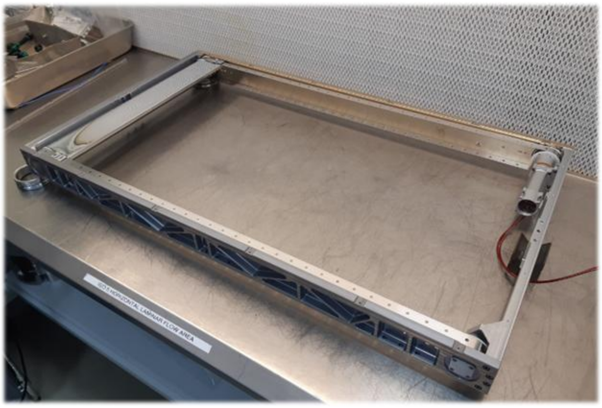

Figure 1-1 Breadboard Mechanism (with covers removed)

With no specific mission allocated, the design needed to be readily scalable to cover radiators of different sizes. A baseline radiator size of 0.6 × 0.36 m (= 0.216 m^2) was chosen to maximise the size of the mechanism while maintaining clearance inside ESR's thermal vacuum chamber. The mechanism is required to be able to operate between temperatures of −150°C to +70°C and survive temperatures up to +120°C, which is representative of lunar surface conditions. A life test target of 9000 vacuum actuations was set, which by ECSS standards, would qualify the mechanism for 3470 actuations in ‘orbit’ (where one actuation is a full opening and closing of the mechanism).

A requirements review was performed early in the project aiming to refine the initial requirements from the Invitation to Tender (ITT) and updating to reflect the feedback from the market survey that was conducted. The market survey identified that the lunar South Pole was the region of immediate interest and thus the requirements and test plan were tailored to reflect this.

2 MECHANISM DESIGN

Two mechanism designs were developed in parallel: a ‘breadboard’ version and a ‘flight’ version. Both used representative materials and processes, however, the flight version used more aggressive weight relief, which was required for structural analysis and to demonstrate compliance with the mass budget of 9 kg/m^2 of radiator area. This was excluded from the breadboard version as no vibration or shock testing was planned at this stage of development. The breadboard mechanism (with top facing covers removed) is shown in Fig 2-1, having been described in greater detail previously [1],[2].

The key elements of the shutter are shown in Fig. 2-1 which shows the whole assembly and Fig. 2-2 which details the drivetrain elements of the system.

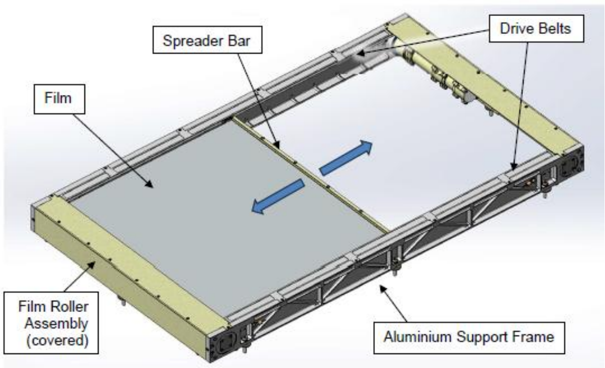

Figure 2-1 Shutter Overview

The mechanism was arranged to house a radiator test plate such that the film was deployed along the length of the radiator. Tensioning of the belts and film were managed to ensure repeatability of opening and closing operations. At one end of the radiator was a spool onto which the film was wound when stowed. At the other end was the stepper motor/gearbox (SMG) used to drive the belt system through a magnetic coupling. The film was rigidly attached to the spool and to a spreader bar, clamped to the belts, which moved back and forth to open and close the shutter.

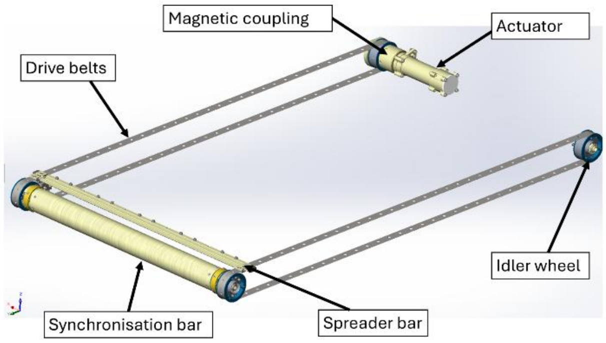

Figure 2-2 Shutter Drive elements

The spreader bar ran in slots in the support frame and was driven by a pair of stainless steel drive belts on opposite sides of the radiator frame, which engaged with pulleys at each end. One of these pulleys was driven directly by the SMG, driving the belt and the spreader bar on that side. The belt drive system with its positive traction and elastic preloading was judged to be the best means of synchronising the roller and motor drive shaft given the expected presence of dust, compared to other design options. The pulley on the spool end of the mechanism was connected to a driveshaft running through the centre of the spool. This was connected to a pulley on the opposite side of the mechanism which drove the opposite belt and hence the other side of the spreader bar. The spool was connected to the driveshaft on flexures which maintained concentricity between the two but allowed for relative rotation between the two. This avoided the need for low friction bearings which would have introduced dust susceptibility in the tensioning of the film. This feature was required as the diameter where the film met the spool changed throughout deployment, unlike the pulley diameter which remained constant. The flexures also provided the force to keep the film in tension. This tension was reacted along part of the length of the two belts. The belts were additionally tensioned by springs, which were installed along the lengths of belts unaffected by the film tension.

The wide-angle rotary flexures connecting the spool to the driveshaft were made of Torlon, which was chosen mainly for its fatigue strength at low temperatures. A flexure pair is shown in Fig. 2-3.

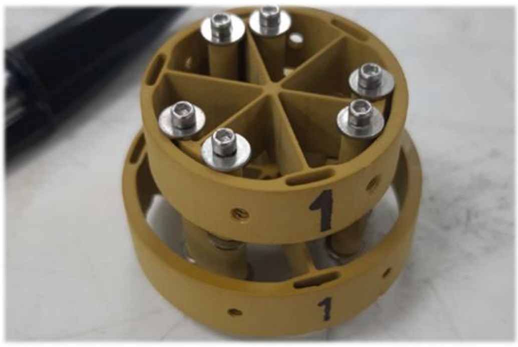

Figure 2-3 Torlon Rotary Flexure

These 'flex pivots' rotate with every operation of the shutter to compensate for the changing radius at which the film leaves the spool; with a 10° pre-installed deflection (to provide initial film tension) the flexures rotate by ±1° across a full deployment of the film; this is shown graphically in Fig. 2-5.

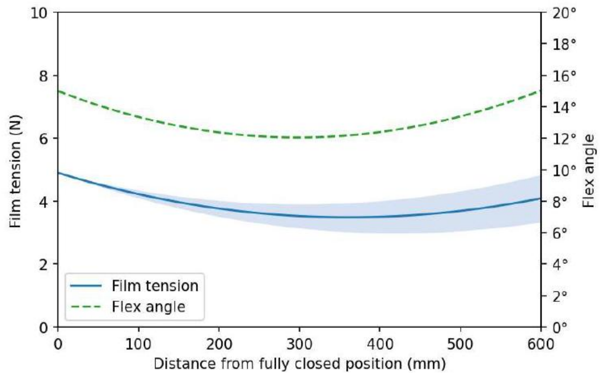

Figure 2-4 Variation of Film Tension and Flexure Angle with Shutter Position

The other element of the LTS which requires tensioning is the belts; this is to ensure that traction is maintained between the belts and the pulley wheels. This is achieved through implementing small tensioning springs between the ends of the belts. The tensioning of the belts is set by adjusting the positions of the axles that support the roller assembly.

The design configuration adopted was also judged to have the greatest potential for future active dust removal features such as using brushes on the spreader bar for radiator cleaning and brushes to sweep the film during retraction.

2.1 Dust Resilient Design Features

A key aspect of the LTS design is to provide resilience to the effects of lunar regolith. It is critical to protect the mechanism tribological surfaces within the SMG and the pulley wheels to ensure the reliable operation of the mechanism.

2.1.1 Sealing Elements

All four pulleys at the corners of the mechanism were mounted on plain bearings made of hardened stainless steel. Plain bearings were selected to be more resilient to debris than ball bearings. These bushing spigots were coated with MoS_2 to provide lubrication over the wide operational temperature range; they also allowed for some level of electrical grounding between the moving components (including the film) and the static structure – this is important to prevent the build-up of any static charge that could attract and retain lunar regolith. The bushings were dynamically sealed to prevent lunar dust ingress and subsequent high friction, where the bushing configuration was intended to be able to withstand a small level of self-generated debris, while keeping out more destructive, highly abrasive regolith particles. The sliding seals took the form of axially preloaded washers made of a low-friction reinforced PTFE compound. Preload was applied by sealed diaphragm springs. While these were inherently dust resilient, the springs had a high, nonlinear stiffness, requiring close tolerancing of spacers which made accurate setting of the preload challenging.

2.1.2 Magnetic Coupling

A critical dust resilient feature of the LTS is a non-contact method of transmitting torque from the actuator to the drive belts. This was achieved by a customised magnetic coupling which allowed the SMG to be completely sealed, eliminating the risk of dust affecting critical gears and bearings in this key component.

The magnetic coupling was based on heritage designs [4] A 10-pole system in samarium cobalt with an outer diameter of 32.6mm was found to provide the optimal combination of mass (<80g), peak torque transmission and stiffness. The design was simulated to establish minimal sensitivity to de-centering forces, and thermal effects.

The coupling itself can tolerate a much higher level of dust ingress given the larger magnetic gaps versus that of traditional motors. This was seen to significantly reduce risk of the actuator and gearhead from any harmful effects of exposure to lunar dust.

3 MECHANISM BUILD

The shutter was built in spring 2024. Whilst the build was ultimately successful, there were a number of issues that were overcome as the build progressed. For the longer sides of the main shutter frame, an aluminium-silicon alloy (DISPAL S260) had been selected for the breadboard as a more readily available alloy versus the rapidly solidified aluminium (RSA) alloy that had been chosen as the flight baseline. The DISPAL material was chosen for its good match in terms of coefficient of thermal expansion (CTE) compared with the stainless steel drive belt material. During machining of one of the sides of the frame the part fractured into two pieces; this happened on multiple machining attempts and so in the end, it was replaced with an aluminium bronze alloy – chosen for its thermoelastic rather than structural compatibility with the original aluminium-silicon alloy. For future iterations it is expected that a different RSA alloy will be chosen, having better elongation properties, so that it is less prone to fracture during machining. In addition, electro-discharge machining will be used to avoid stress build-up where the design calls for weight relief that is highly asymmetric, which can otherwise result in bowing of this high aspect ratio part.

Other lessons learned during assembly of the shutter include the shimming of the preloading springs which proved to be time consuming, and alternative concepts have been proposed to relax tolerance sensitivity. In this way, design changes have been identified that will increase the ease and efficiency of assembly.

4 TESTING

4.1 Test Logic

The test logic for the LTS is shown in Fig. 4-1.

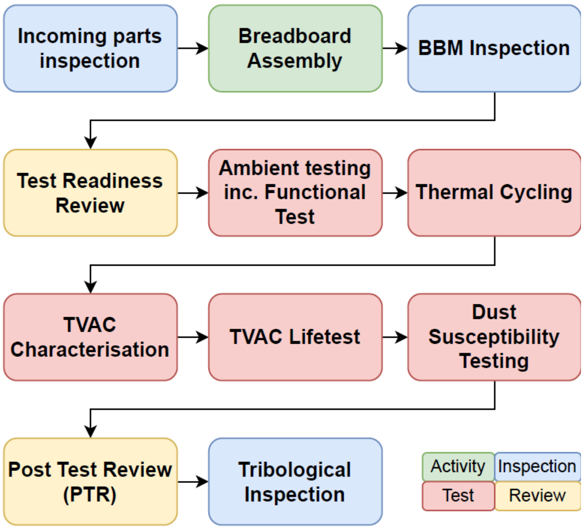

Figure 4-1 LTS Test Flow Logic

The test logic was established to demonstrate and characterise the key functions of the mechanism i.e. dust resilience and thermal performance. Mechanical environment tests were not planned for this breadboard model.

4.2 Test Facility

A bespoke test facility was established at ESR with the principal aims of:

- Driving the shutter across the required temperature range (−150 °C to +120 °C)
- Providing a representative thermal environment to allow characterisation of the thermal performance of the shutter.

The shutter thermal tests were performed inside a dedicated test rig installed in a 600 mm diameter vacuum chamber. The shutter was mechanically supported in a framework resting on the chamber base and insulated from the chamber and the support structure by polymeric isolating mounts. The shutter was constrained within the chamber but not held rigidly to avoid issues which could result from relatively large CTE displacements when cooling to low temperatures.

The test rig supports a central black painted radiator plate which the shutter is positioned around. This is conductively isolated from the shutter (as would be expected for any flight opportunity). A large high emissivity cold target was positioned immediately in front of the shutter to provide a simulated view of deep space. The radiator, shutter and the cold plate all contained heaters, allowing each one to be heated independently of the other. To facilitate cooling, a Gifford McMahon cryogenic coldhead was integrated into the chamber; this could be connected by copper thermal straps to either the cold target and/or the shutter.

The test facility CAD and hardware are shown in Fig. 4-2 and Fig. 4-3 respectively.

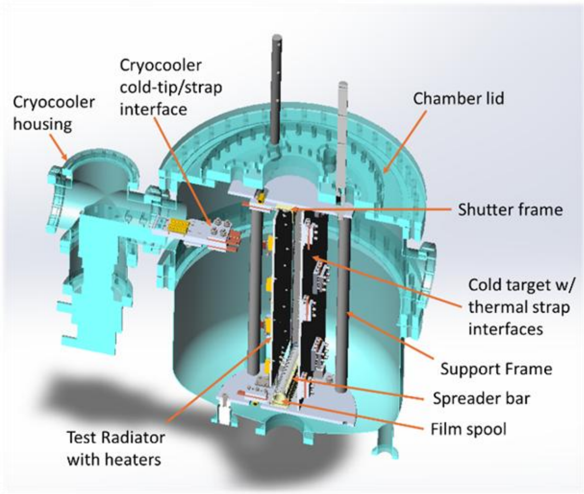

Figure 4-2 CAD Image of Test Facility

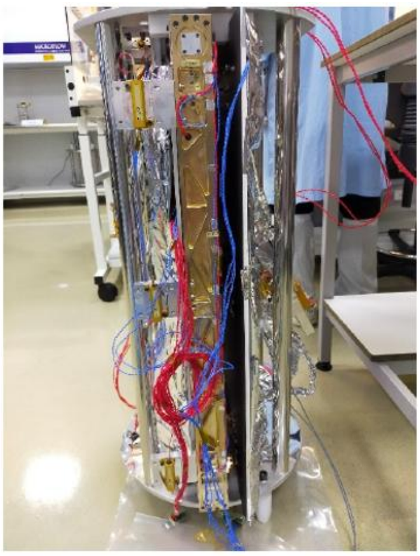

Figure 4-3 Test Facility

4.3 Functional Testing and early characterisation

The initial functional tests were performed in air, in the vertical orientation. The initial success criteria was simply a successful actuation of the limit switches at the end positions, which was achieved.

Testing was then expanded to cover additional characterisation tests. This included operation in different orientations with respect to gravity, which showed no variation in performance. Motorisation margin testing was performed by reducing the current supplied to the motor, thus restricting its output torque. Successful operation of the LTS at 62 mA (in air) demonstrated compliance with the motorisation requirements of ECSS [3].

Further characterisation included assessment of the repeatability of the shutter in terms of motor steps and the position of the spreader bar. This showed a backlash of 2–3 mm between moving in the opening and the closing direction. The vast majority of this was attributed to the compliance in the non-contacting magnetic coupling and was expected.

Due to the use of MoS_2 lubrication in the motor and gearhead (which is sensitive to operation in air), all operations of the shutter in air were planned and recorded. With in-air characterisation competed, the shutter was installed into the test facility for vacuum testing.

4.4 Thermal Cycling

Thermal cycling testing was performed between −150 °C to +120 °C. Performance at the hot operational temperature was demonstrated by a successful functional test at +70 °C following a 2-hour plateau at the hot non-operational temperature of +125 °C. After a dwell at the low non-operational temperature of −150 °C a functional test was commanded, and some initial issues were observed. Through a view port in the vacuum chamber, it was observed that whilst the motor and drivetrain appeared to be functioning, there was an issue with the belts slipping and the spreader bar becoming misaligned. It could be seen that the belts were no longer tensioned and there was an obvious bowing of the belts. A review of the evidence identified that this was a result of the thermal contraction of the shutter frame with respect to the belts. This effect was considered in the design of the shutter; however, only an isothermal case was considered. With the belts and shutter at the same temperature the small difference in coefficient of thermal expansion (CTE) between the belts and the frame would not cause a loss of tension. With the belts only having a small thermal contact conductance to the rest of the structure (which was exacerbated as the belt tension and hence contact pressure dropped) it was likely that the belts were warmer than the rest of the structure. It was this temperature difference that caused the belts to become loose and lose traction.

The shutter was then warmed up, and a nominal functional test was performed at −50 °C without any issues. No long-term effects were observed, and the performance of the shutter was fully recovered after warming up.

The remainder of thermal cycling was completed successfully between −50 °C and +70 °C.

4.5 Thermal Performance

A critical aspect of the testing was to establish the shutter thermal performance i.e. how effective is it at controlling the amount of heat rejected by the radiator. A more detailed review of thermal aspects was presented in a recent paper [3], while a summary is provided herein.

The key performance indicator is the Turn-Down Ratio (TDR); this is the ratio of heat rejected on the open position to the heat rejected in the fully closed position; it can also be expressed as an effective emissivity. To achieve these measurements, the shutter and the radiator plate were maintained at the same, fixed temperature, with the cold target cooled as much as possible. With the shutter in the fully closed position, the heater power required to maintain the radiator temperature was measured. The shutter was then opened to different positions and the system was allowed to settle to a steady state. With a greater view factor between the radiator and the cold target, the increased heater power needed to maintain the constant temperature of the radiator was recorded. By maintaining thermal equilibrium between the shutter and the radiator, the additional heater power required is equal to the additional heat being rejected by the radiator.

Thermal performance tests were performed with the radiator at three temperatures: −30 °C, +20 °C and +50 °C; these were chosen to encompass the likely range of operational temperatures of the radiator for lunar applications.

In the ambient case, the heat emitted from the radiator plate varied from 6.3 W to 55.6 W between the closed and open positions. In the cold case, this was 11.7 W to 73.9 W and then for the hottest case this was 0.4 W to 25.3 W.

The estimated turn down ratios are around 10–12 for the ambient and hot case; the cold case turn-down ratio is calculated as 80, however this relies on the measurement of a smaller heater power so has a much larger measurement uncertainty. Overall, the estimated turn-down ratio of 10 is considered slightly conservative due to an increase in the cold target temperature that was observed as the shutter opened; this could be improved for future tests.

Fig. 4-4 shows the results of the thermal performance test expressed as the effective emissivity of the radiator.

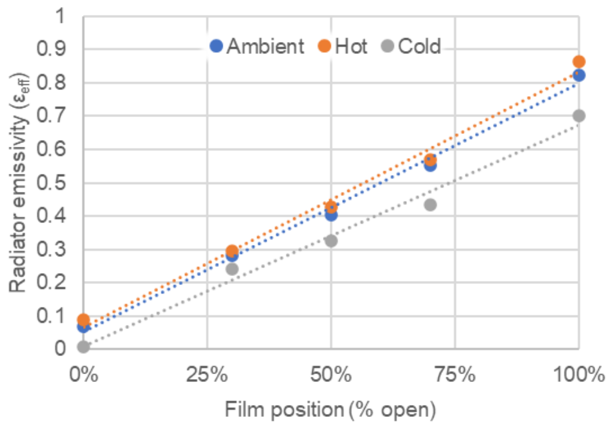

Figure 4-4 Radiator effective emissivity for different shutter film positions

The results show that the concept is highly capable in varying the heat rejection of the radiator. This is the key functional requirement of the shutter, and the results were in line with the predictions from the thermal analysis.

In addition to the constant temperature tests described above, tests were performed where a constant heater power was applied, and the temperature change of the radiator was measured for different shutter positions. The radiator temperature showed a high dependence with the shutter position and for these tests a 1 % (or 6 mm) shift in the shutter equated to a 1 °C change in the radiator temperature.

Overall, the performance tests were considered highly successful. Not only did the shutter demonstrate high turn down ratios which could be mission enabling for lunar applications, it also proved itself capable of providing accurate thermal control of the radiator.

4.6 Lifetime Assessment

A full life test (factored in accordance with [6] was not planned on the breadboard; this was because the key tribological elements had been subjected to a full factored life test during earlier component level tests i.e. axial bushings. A lower level of life test assessment was made however, and as per the test plan this involved completing 2000 mechanism open/close cycles which equates to ~20 % of the ECSS factored lifetime. With the sensitivity to using MoS_2 in laboratory air it was decided to include the full amount of factored on-ground, in-air cycles for the breadboard test campaign; this would ensure that any impact of the in-air running and premature lubricant degradation could be established at an early stage.

4.7 Dust Testing

Dust susceptibility testing was performed at the University of Glasgow large-volume dirty vacuum facility [5]. The lunar simulant selected for the test was LHS-1 from Space Resource Technology. This simulant was chosen for its representativeness of regions of interest on the lunar South Pole as well as its relatively modest cost.

The intention of the dust test was to provide a coarse assessment of the LTS' resilience to operating under dusty lunar conditions. Dust exposures were intended to be representative of lunar events such as rovers or astronauts passing by, as well as larger dust events such as the landing or taking off of lunar spacecraft. A total of four dust events were planned: three light exposures targeting a deposition rate of 10 µg/cm^2, and a single exposure targeting 100 µg/cm^2. Functional tests and motorisation margin tests before and after each exposure would allow characterisation of any impact on the mechanism.

A schematic of the test set-up is shown in Fig. 4-5.

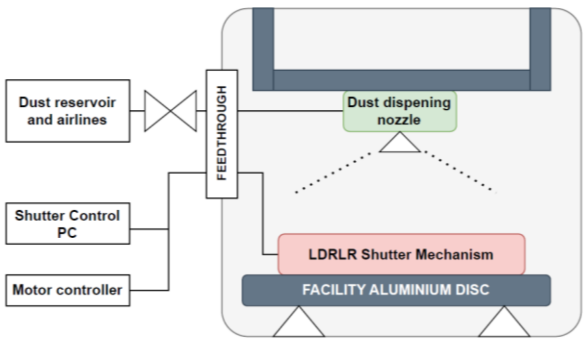

Figure 4-5 Schematic of Dust Testing Facility

A bespoke dust delivery system was established by ESR which used a dust reservoir and solenoid valves on the air-side of the vacuum chamber. Pulsing of the valves allowed the vacuum of the chamber to suck in a pre-measured quantity of air/dust mixture into the chamber. Dust was ejected through a dispensing nozzle and dispersed within the chamber.

An arrangement of petri dishes within the chamber allowed for an amount of the dust to be captured and weighed – this would provide confirmation of the dust quantity actually delivered.

Testing was carried out successfully with all planned dust exposure events achieved. Functional tests between the dust exposure events were successful. Images captured during the dust tests are shown in Fig. 4-6 and Fig. 4-7.

Figure 4-6 Dust Plume from Dust Exposure #4 (heavy)

Figure 4-7 Thermal Film at the end of dust testing

5 IDENTIFIED IMPROVEMENTS

5.1 Testing

Whilst testing was successful, it is recognised that for any additional mechanism tests improvements would be needed to both the internal test facility and to the methodology regarding dust testing.

In defining and performing the dust testing, it became clear that, certainly within Europe, this is very much a nascent capability. With a number of large facilities expected to become operational soon (i.e. the Dusty Thermal Vacuum Chamber at the European Space Resources Innovation Centre (ESRIC) facility located in Luxembourg), ESR had to establish its own methodology and test parameters. This was a very coarse test, which whilst suitable for a breadboard would need to be significantly refined for any flight opportunity. It is expected that future dust tests on mechanism units would be performed at a dedicated test facility that is fully experienced in delivering specific dust deposition rates.

The dust testing also raised a practical issue. For the breadboard, the dust test was left until the end of the test campaign. This was for two reasons; firstly, it was considered to be the riskiest part of the test and it would be beneficial to perform as much mechanism characterisation in advance of the dust test in case of a significant test failure. Further, it was seen to be important to fully characterise a clean mechanism as the initial baseline reference. The other, and more practical reason, was that the mechanism would be contaminated with dust simulant afterwards and would pose issues for testing in ESR's clean vacuum test facility. This raises an interesting problem; as with vibration tests which are used to pre-condition bearings before a life test, it would be desirable to perform a mechanism dust test prior to or ideally simultaneously with the life test. This is because the presence of any dust is going to potentially impact the performance and lifetime of any tribological element such as sliding seals and could impact the results of the life test. There are two options to achieve this; perform the mechanism life test at an external specialist dust test facility or the mechanism provider will need to provide its own dust compatible test facility. Both options are expected to be expensive and the test logic in this regard should be established and agreed at the proposal stage.

5.2 Shutter Design

The low temperature tests identified an issue with retaining the belt tension at the lowest operational temperatures. The problem was seen to be exacerbated by the high cooling rate, which generated unrealistic gradients. With the issue being understood, design and test modifications in order to remedy this have been identified which will improve both aspects. By increasing the length of the belt tensioning springs, a greater variation of the spring extension can be tolerated. With greater compliance, the belts will be able to withstand a larger contraction of the shutter before becoming off-loaded and losing traction. Design changes to improve the ease of assembly of the mechanism have also been identified. Better control of ramp rates in cooling steps will also be implemented via the test cold head heater operation to slow down cooling and limit resulting gradients.

6 NEXT STEPS

The target Technology Readiness Level (TRL) for the shutter was originally TRL3. During the course of the project, a contract change was approved that improved the representativeness of the actuator and the magnetic coupling; thus, at the end of the programme the LTS was agreed to be at TRL4.

An important aspect of the shutter performance that was not verified by test in the breadboard campaign was the structural performance and the ability to withstand launch vibrations. The design of snubbers and selection of snubber clearances should be revisited considering any updates to specified vibration levels. A vibration test should be performed early in any future program and would provide derisking of critical parts of the mechanical design. One example is the concern of fatigue on the flexures within the roller assembly caused by vibration (if there is a coupling of flexure frequency and input). This must be characterised as part of future activities. After a vibration test, a detailed inspection would need to be performed on the flexure elements to specifically look for signs of fatigue. Testing is the preferred approach for future development activities although some level of early analysis may also be beneficial (to be followed by a test and inspection of flexures and tribological elements in particular). The implementation of a vibration test is considered the next logical step in the development of this device.

The lifetime of the selected actuator has not been fully verified with the selected MoS_2-202 sputtered lubricant from ESTL (all previous tests at motor level have been performed with the standard grease lubricant). The lifetime achieved on the breadboard was 1.44 million revolutions (with no apparent degradation seen in performance at the end of life) while a fully factored life test would require 7.2 million cycles. This is recognised as a potentially challenging requirement for the dry lubricant. A life test on the actuator would allow confirmation of the number of mechanism actuations that could be achieved; it should also be coupled with a vibration test for full validation of the actuator lifetime.

7 CONCLUSIONS

The Lunar Thermal Shutter has been designed, built and tested by ESR Space with support from Spacemech Ltd, Almatech and Space Science Solutions Limited. The mechanism performance was in line with requirements in all aspects, except for the low operational temperature. This issue has been understood, and design updates have been identified that are expected to solve the issue.

The thermal performance tests exceeded expectations and requirements. The turn-down ratios that were measured show that the concept will provide significant benefits to lunar applications, especially those at the lunar South Pole with potentially long lunar winters. With the improved thermal control and proven dust resilience offered to lunar payloads, it will be possible to reduce the power demands for survival heaters; this in turn this will reduce the requirements for energy storage and generation i.e. batteries and solar panels. Overall, the 2 kg mass of the shutter is expected to provide a net reduction in system mass.

In addition to the thermal benefits, the dust resilient aspects of the shutter were successfully demonstrated through a coarse dust test. The mechanism performed normally after several dust exposures and a post-test inspection found that dust had been prevented from entering the tribological surfaces that were being protected. The shutters aluminised film provided a good protection for the radiator against the dust, while not completely sealed.

The LTS breadboard model has shown significant promise as a thermal control device and the further developments that have been identified will allow the technology to be de-risked and raised up the TRL ladder.

8 ACKNOWLEDGEMENTS

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