THE DEVELOPMENT OF A SELF-RESETABLE, LOW-SHOCK HOLD-DOWN AND RELEASE MECHANISM

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KEYWORDS

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ABSTRACT

Satellite systems are often equipped with deployable structures. Such structures (e.g. solar arrays) are stowed and preloaded to the structure of the satellite prior to launch. The preloading and the release are handled by hold-down and release mechanisms (HDRM). Many hold-down and release mechanisms are nowadays commercially available. The release bolt of the mechanism is the interface between the deployable structure and the satellites body. This bolt is released for deployment of the structure. Usually this bolt can be either fractured by a shape-memory alloy cylinder (SMA), by explosives, or it can be freed by internal kinematics to remove blocking elements holding the bolt in place to allow separation of the I/F. Those release methods are widely implemented in commercial products.
The new HDRM technology developed at DLR termed CREAM (Collet Release Mechanism) omits those methods and instead fixes the bolt through a frictional mechanism. Several major improvements can be achieved by this strategy: simplicity in the design, low-shock characteristics or self-resetability. The frictional locking mechanism is realized based on a self-locking clamping device used widely in industry, but tailored to the needs of space applications. This mechanism allows unique simplicity in the handling of the device.
This paper will start with a state-of-the-art review on existing hold-down and release mechanism. This shall identify individual advantageous and drawbacks of the different technologies. The major requirements for the development of CREAM are outlined afterwards. It further describes the CREAM technology in principle and continuous with the design description of the 1.5 kN CREAM HDRM model. The paper describes the prequalification of this unit and the outcome of the test campaigns. The commercialization process together with the industrial partner, DCUBED, is outlined at the end of the paper.

1. INTRODUCTION

Satellite systems are often equipped with deployable structures. Such structures (e.g. solar arrays) stowed folded and preloaded to the structure of the satellite prior to launch. The preloading and the release are handled by hold-down and release mechanisms (HDRM). Many hold-down and release mechanisms are nowadays commercially available. The release bolt of the mechanism is the interface between the deployable structure and the satellites body. This bolt is released for deployment of the structure. This paper focuses on non-explosive HDRMs, which purely free a release bolt on command. Usually this bolt can be released either by fracturing through a shape-memory alloy cylinder (SMA), by a split-spool device, or it can be freed by removing blocking elements through an internal kinematic. Those release methods are widely implemented in commercial products.
The new Collet Release Mechanism (CREAM) technology developed at DLR omits those methods and instead fixes the bolt through a frictional mechanism.

2. STATE OF THE ART REVIEW

Many commercial HDRMs are present nowadays. Three groups of actuators are widely used in the field of small satellites and are discussed here: Split-spool devices, fracture bolt devices and mechanical un-locking release devices. Hereafter a short review of the single groups of HDRMs is given.

2.1. Split-spool devices

Split-spool devices are widely used in space industry in systems at which very quick release times are required. This is especially needed at the synchronised release of several objects at the same time [3]. Split-spool devices are based on a spool which encloses the release bolt and a pair of metallic shells. The spool itself maintains its shape by being secured using a set of two fuse wires (one for main, one for redundant firing). This assembly is arranged within a separate housing. The shape of the metallic shells and the release bolt prevents the bolt from moving out of the housing, if the shells are held into position by the spool. The fuse wires of the spool are powered with high current (e.g. min. 2 A

[2]) for the initiation of the release. The high current leads to melting and rupture of the fuse wire, which leads to a large radial extension of the spool. The metallic shells within the spool are therefore no longer kept in place and move away from the release bolt. Once this happened the release bolt can move out of the housing (from [1] and [3]).

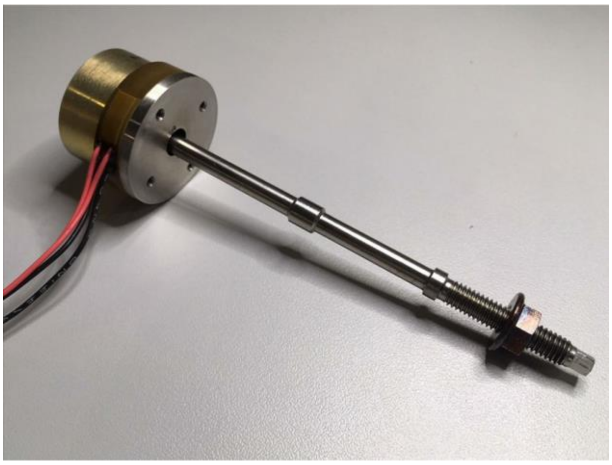

Figure 1 MASCOT hold down and release mechanism (HDRM) comprising of a non-explosive actuator 9100 from NEA® Electronics, Inc. and a custom-made separation bolt (text and picture from [4])

The major advantages of the split-spool based HDRMs are the very quick actuations times [2] and the reliability due to the simplicity in the design. However, split-spool devices need a full refurbishment of the spool after release. It is needed to replace the actuated spool by a completely new one as each spool can only be used once. The refurbishment requires therefore the dismounting of the HDRM from the system. At some devices the disassembly of the HDRM itself and the refurbishment can be done on-site by trained staff. At others it is required to send the units in for refurbishment [5].

This strategy of refurbishment drives the financial and time effort for single actuations significantly. A new spool (or a set of spools) needs to be purchased and integrated after each actuation of the HDRM [2]. This omits repetitive testing of mechanisms in the flight configuration. One can argue that the very high reliability of the HDRM does not need intensive testing. This can be accepted on HDRM level testing. But the verification of a full deployment system requires a fully flight-like configuration, which would include flight-like HDRMs. This is especially important for separation systems, at which design confidence can only be gained through intensive testing. This problem can of course be tackled by accepting a higher risk on mission side.

Furthermore, the split spool technology does not allow for a test-as-you-fly approach as the spools cannot be tested twice a priori. But this is considered a minor issue, as the reliability of the HDRMs is proven to be very high. Therefore, the increased mission risk is only minor.

2.2. Fracture bolt mechanisms

Fracture bolt mechanisms are commercially available under the trade name “Frangibolt (EBAD)” (see also Figure 2 from [8]) and “TRIGGY (Nimesis)” [6]. This type of mechanism is based on a fracture bolt, which is fractured by a shape memory alloy (SMA) cylinder for actuation. The SMA cylinder is compressed in ambient environment prior to installation. For actuation the SMA cylinder is heated-up to its transition temperature, which makes the cylinder expand significantly. This expansion leads to an elongation of the bolt beyond its limits, which ruptures the bolt.

Figure 2 Close-up view on a EBAD Frangibolt (picture from [8])

The configuration of the different commercially available products can be simplified described as follows [6]: The body of the HDRM consists of an SMA cylinder with an attached heater and temperature sensor. The whole assembly is protected by a silicone rubber glue jacket against the environment. The SMA cylinder is compressed by external mechanical ground support equipment (MGSE) prior to installation. For final assembly the fracture bolt is feet-through the HDRM and the separable parts. Finally, the fracture bolt is preloaded by torqueing. The fracture bolt itself has a notch at which the bolt will rupture. This notch is required to ensure a defined location of rupture and to allow a certain stiffness of the fracture bolt itself.

This HDRM is typically used at application at which exact timing and quick actuation is not required. Usually the heating of the SMA cylinder to its transition temperature takes about 30 s [8] at ambient. The heating time is increased at cold and decreased in hot environment as the temperature between starting temperature and actuation temperature changes. Therefore, the actuation time varies in the range of seconds for the different thermal environments. This is making a synchronized activation of several fracture bolt HDRMs nearly impossible.

These type of HDRMs emit high shock levels by design. The shock levels can even be higher than the separation shocks from the launch [9]. The fracture bolt brakes and emits high energy transiently into the system. This energy equals the strain energy to brake the bolt. This energy is significantly higher than the strain energy stored in the fracture bolt for preloading the system. The emitted energy is therefore a priori higher than in other HDRM types as those would only store the strain energy to preload the system. High shock levels might endanger adjacent instruments. The use of a fracture bolt mechanism close to e.g. optical instruments requires a detailed study on the shock levels at the sensitive instrument. It might even be necessary to add damping elements in the design, which drives complexity and mass.

The effort of resetting after actuation is considerable as the SMA cylinder of the actuator needs to be compressed to its old configuration after activation. This requires dismounting of the device, as it needs to be compressed by external equipment (This equipment is usually installed on a work bench due to its size). Also, a new fracture bolt needs to be used each time. The resetting of the HDRM requires about same time effort as the resetting of an on-site resettable split spool device. But the fracture bolts are more affordable due to its simplicity than spools of split spool devices.

The major advantage of this type of mechanism are its very small size and its easy handling. This makes the integration into systems at which the available space is minor easy.

2.3. Mechanical un-locking hold-down and release devices (MU-HDRM)

This category of mechanisms is introduced here to categorize all HDRM types, which are based on an internal kinematic to maintain the release bolt within the mechanism. Hereafter one principle is explained to illustrate this category. There are also other principles available, but this paper focuses on one example for illustration: Form-locking of the release bolt is e.g. realized by steel balls, which keep the release bolt into position. Any motion of these steel balls is omitted by a blocking adjacent structure. Therefore, the release bolt remains in its position during launch. The steel balls are free to move once the blocking adjacent structure was moved into a different position. This motion can be initiated by e.g. SMA wires/springs or paraffin. This frees the form-locking between the release bolt and the steel balls. The release bolt is free to move afterwards. Many different MU-HDRMs were developed in the past. Some of them were tailored to a specific system and are therefore usually not commercially available. Others were designed as a product for the space market and are available. Several different devise are available: [11] [12] [13] [14] [15].

Those mechanisms are usually tackling the disadvantageous of the two previously discussed designs: Reset-ability / -costs and shock imitation.

The effort of resetting these devices is usually smaller than on other devices. In best case, it can remain attached to the structure for the reset. For very small devices [15] no additional tool is needed for the reset. Larger devices ([10] [11]) require an external tool and access to the HDRM for the reset. Although this is still a constrained for the integration of these devices into a larger system, it is still less effort than previously shown on other devices. Furthermore, the discussed way of resetting does not lead to further financial costs after an activation. The shock imitation of these devices can be reduced to acceptable levels (<1000 g @ 1000 Hz, e.g. [14]). The energy emitted transiently at the time of release equals the elastic strain energy from the stored preload. Furthermore, the internal mechanism might allow a smooth release, which distributed the transient energy into a larger time scale.

This kind of mechanisms usually consume more volume or mass as other HDRMs with same preload force. This is due to the necessity to integrate an internal kinematic to un-lock the release bolt. This kinematic usually also needs several complex machined parts. This leads to larger effort in manufacturing, quality inspection and integration. Resulting in higher manufacturing costs per unit.

MU-HDRMs are beneficial to use for time critical separations (even synchronized), low shock applications and applications at which a large number of tests are required for verification.

3. REQUIREMENTS

The requirements are based on the state-of-the-art review of existing HDRM types and experiences from flight-mission in the past. The requirements shall ensure that the developed technology is superior to existing MU-HDRM types to compensate their drawbacks in terms of mass and volume. Hereafter only the key requirements are shown for simplicity.

3.1. Scalability

The first technology demonstrator shall be designed for a preload size of 1.5 – 2 kN. A second technology demonstrator shall be sized for 4 – 6 kN preload. This shall show scalability of the technology.

3.2. Permanent Installation to the System

The HDRM shall be design to allow a permanent installation to the system. This means that the HDRM is installed once during integration and no further touching is needed. This enables new ways of installation. It is possible to permanently install the HDRM into a sandwich structure by potting. That would reduce the required volume and reduce complexity.

3.3. Resetting

Resetting of the HDRM shall be as simple as possible. Any external MGSE for resetting shall be omitted, as the access to the HDRM might be limited. Furthermore, it shall be avoided to touch the actuator for reset. The absence of MGSE for the reset and touchless resetting is further considered a self-resetting behaviour.

3.4. Low-shock Actuation Characteristic

The actuation shall not lead to excessive shocks. The target is to limit the shock at actuation to less than 1000 g. This is considered a convenient shock for most instruments.

3.5. Preload-to-Volume and Preload-to-Mass ratio

The given preload sizes (1.5 kN and 5 kN) are usually used in CubeSat or SmallSat missions. Available volume and mass are limited at those missions. Hence it is necessary to have a design, which enables high preload-to-volume and preload-to-mass ratios. A performance analysis was used to derive a compatible volume and mass. This analysis uses the available datasheets from several commercial HDRMs and derives the volume to preload and the mass to preload ratio. Those are hereafter termed specific volume and specific mass. Both ratios are arranged to each other in Figure 3 (for < 2 kN preload) and in Figure 4 (for < 6 kN). The x-axis is showing the specific volume and the y-axis is showing the specific mass.
The HDRM with the best specific volume and specific mass is the one at the bottom left in the graph. The area of acceptable ratios in this graph is encircled in red. At this area all split spool devices and the fracture bolt mechanisms are present. A later design laying within this area is therefore capable in terms of mass and volume with other units.

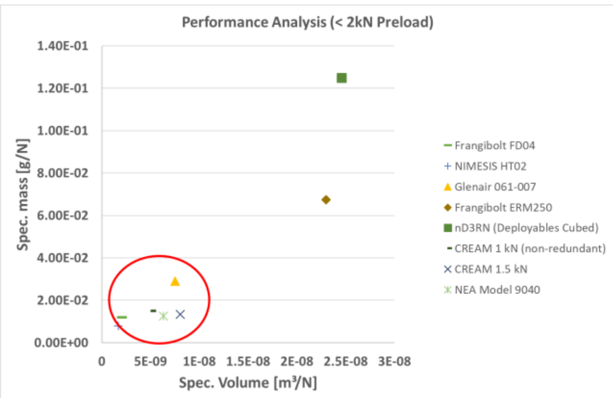

Figure 3 Performance analysis for HDRM with a preload < 2 kN

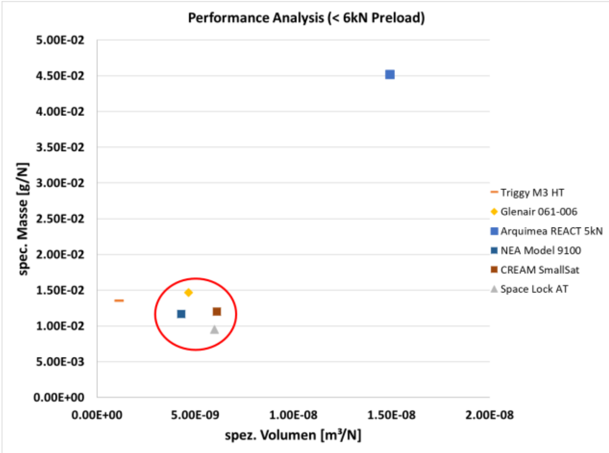

Figure 4 Performance analysis for HDRM with a preload < 6 kN

3.6. Low-cost

The design is intended to be commercialized through an industrial partner. Hence it must be superior or as good as other HDRMs in terms of financial effort for manufacturing and integration. This shall be achieved by using few, simple parts, which can be machined by industrial standard milling machines. Also, it should be tried to use commercially available industrial standard products for further simplification.

3.7. Actuation Time

Actuation time is always an important aspect of HDRMs. Split-spool devices and some MU-HDRMs have very fast actuation times (< 0.1 s). Certain applications might require this very accurate and short timing. But there are also a lot of application, at which longer activation times (few seconds) can be accepted. Therefore, it was decided that the HDRM shall have an activation time of < 5 s.

4. DESIGN DESCRIPTION

4.1. Principle of the CREAM Technology

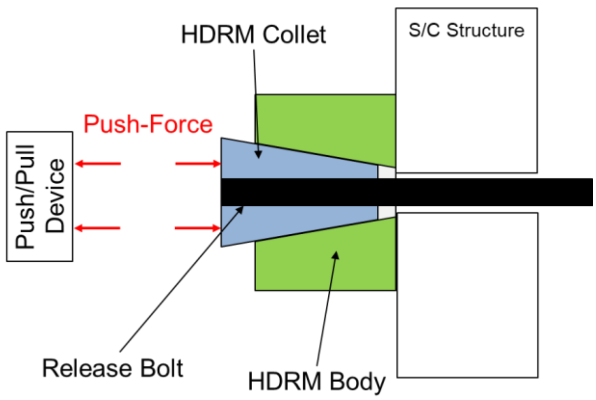

Figure 5 Overview of the design principle of CREAM (locked state)

Figure 5 gives a principle overview of the CREAM technology. The major parts are the push/pull device, a collet and the body structure. The body is the interface to the spacecraft and mechanically mounted to its structure. This can be realized by screws, or even by gluing. A commercial collet is installed to the cone at the centre of the body. The push/pull device is continuously pushing onto the collet in locked state. This device is an SMA driven actuator, which pushes onto the collet if it is not powered and pulls on the collet at activation. The release bolt is located within the collet. The collet and the release bolt are in contact to each other through a frictional mechanism. The frictional pairing is chosen such that a self-locking effect is present: Pulling at the release bolt leads to a motion of the collet into the body, which leads to further radial forces on the release bolt. Higher radial forces allow higher pulling forces before slipping occurs. This effect is self-amplifying and self-locking.

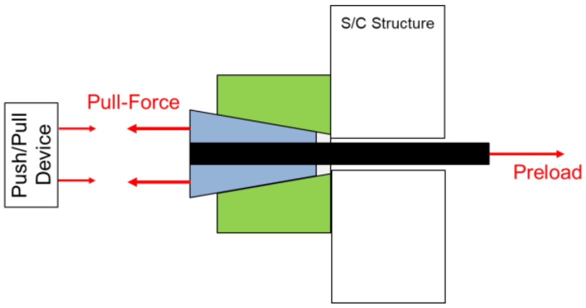

Figure 6 Overview of the design principle of CREAM (un-locking)

Figure 6 shows the un-locking behaviour of the CREAM technology: The push/pull device is activated and starts pulling on the collet. At the same time the preload is acting on the release bolt. The pull force and the pull stroke are chosen such that the collet can be pulled out of the cone against the preload present at the interface. This requires high forces and a large stroke to account for all elastic deformations at the body. Once the pull force is acting on the collet it starts slipping towards the push/pull device. At this moment the radial force on the release bolt is decreased significantly leading to a release of the bolt.

4.2. Design of the CREAM 1.5 kN Unit

The 1.5 kN CREAM HDRM has a cylindrical shape with a diameter of 27 mm and a height of about 21 mm. Figure 7 shows a detailed view on the engineering model (EM) unit from the point of view of the mechanical interface to the spacecraft structure. The mechanical interface is realized by two M2 screws located next to the centre. The electrical interface is located at the opposite side. Four wires are present: two for the main heating and two for the redundant heating. The wires are located at the brim pointing outward parallel to the centre of the HDRM.
Table 1 shows the baseline specification for the qualification models of the CREAM 1.5 kN HDRM. Two supply voltages for this HDRM are planned to be qualified: One for 9 V supply voltage (CubeSats) and one for 20 V supply voltage (SmallSats). The resistance was adjusted to not exceed a current draw of more than 2 A. The variation of the supply voltages does not impact the mechanical interface. The units have a redundant SMA winding included. The total mass (without harness) is about 20 g.

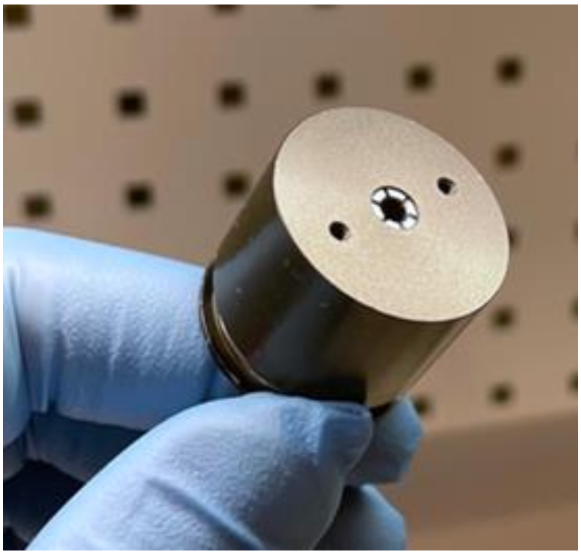

Figure 7 CREAM 1.5 kN EM unit

Table 1: Specification of the CREAM 1.5 kN unit

	CREAM-1.5kN-9V	CREAM-1.5kN-20V
Preload [kN]	1.5	
Supply Voltage [V]	9	20
Elect. Resistance [Ohm]	4.5	20
Mass [g]	20	
Volume [mm³]	27 (dia.) x 21	
Redundancy	Yes	

Installation and resetting:

This mechanism allows unique simplicity in handling. At first it is mechanically permanently installed to the S/C by the aforementioned M2 screws. Afterwards the separable joint can be closed and the release bolt can be installed to the HDRM. This is done by directly pushing the release bolt into the HDRM. If a zero-force installation is required, the HDRM needs to be powered during insertion. This moves the collet out of the cone, which reduces the installation friction. Preloading of the HDRM can be done directly afterwards. This way of resetting allows a permanent installation of the device to the spacecraft. The loading/release cycle at full preload can be repeated > 30 times without any refurbishment.

5. PREQUALIFICATION

Final qualification is currently ongoing. Beforehand a set of de-risking tests were performed:

- Ambient activations
- Mechanical-dynamical testing
- Thermal-vacuum cycling and activation

A short overview of the tests and the results are given hereafter.

5.1. Test Adapter

All tests were performed with the same test setup. Figure 8 shows the test adapter. The adapter consists of three aluminium plates, which can be changed in their configuration such that mechanical excitation in different axis is possible for the mechanical testing. The CREAM HDRM is rigidly installed to the horizontal aluminium-plate on the bottom side as previously discussed. The release bolt consists of a 3 mm rod attached to an M8 screw with a nut. A force gauge with bearing is located between the nut of the release rod and the horizontal plate on the top side. The preloading is achieved by turning the nut, while counteracting on the release bolt with a spanner. This shall prevent any torsion on the HDRM or the assembly.

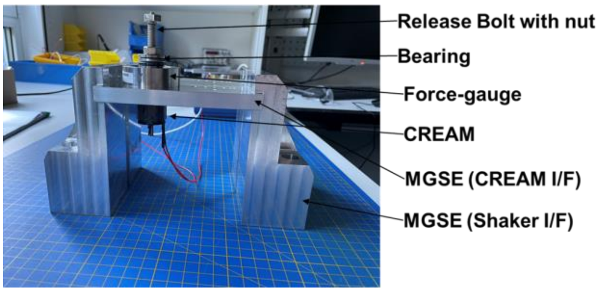

Figure 8 Universal test adapter for ambient and TVAC tests

5.2. Ambient Release

Figure 9 shows a typical preload and release cycle of the CREAM HDRM. The preload was applied as described before by torqueing the nut at the release bolt. The preload drops slightly after it was applied to the bolt. This behaviour is currently further studied in long-term stowage tests. The preload increases to about 1.7 kN at the activation. The activation time at ambient conditions was about 2 s. Several successful activations were performed with this setup.

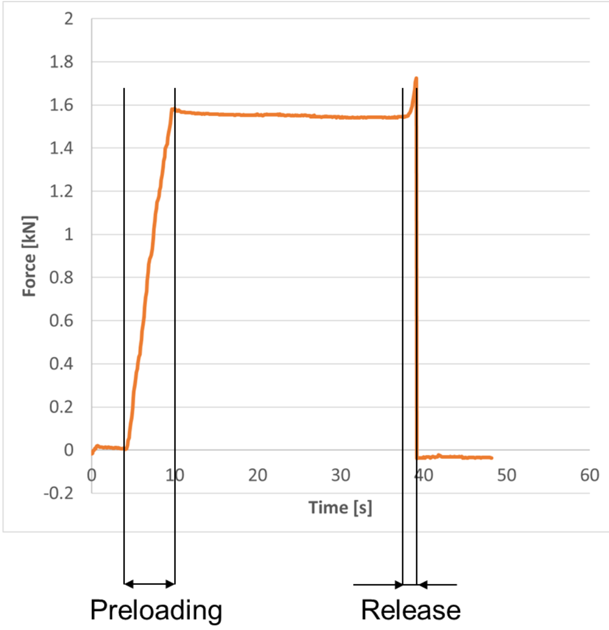

Figure 9 Typical Preloading and Release Cycle

5.3. Mechanical-Dynamical Testing

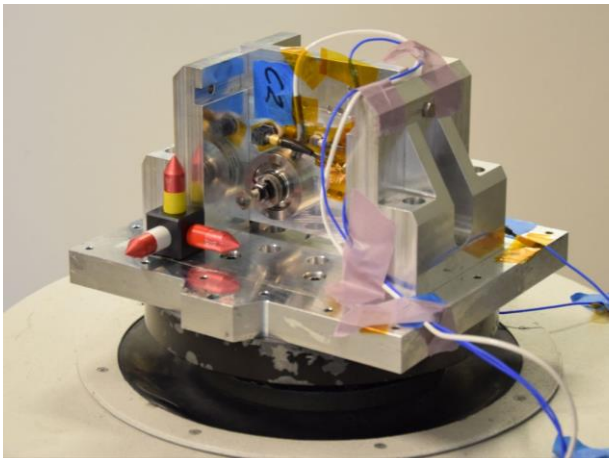

Figure 10 CREAM vibration test configuration

The vibration test of the CREAM HDRM was performed at the vibration test facility in the DLR Institute of Space Systems. The HDRM was mounted on the MGSE with the pre-loaded of 1 kN. Then, the test object was subjected to the sinusoidal and random vibration for each axis. The level of the sinusoidal and random vibration is according to the standards of the component qualification [16]. During the vibration test, the load on the HDRM was monitored and it was confirmed that the applied pre-load was maintained. After all the vibration test cases, the CREAM was successfully released under ambient conditions.

5.4. Thermal-vacuum activation

The thermal vacuum test was performed in the calorimetric chamber in the DLR Institute of Space Systems. The CREAM HDRM was installed on the MGSE with the preload of 1 kN and this assembly was mounted on the temperature controllable cold plate (Figure 11). In this test, the HDRM was

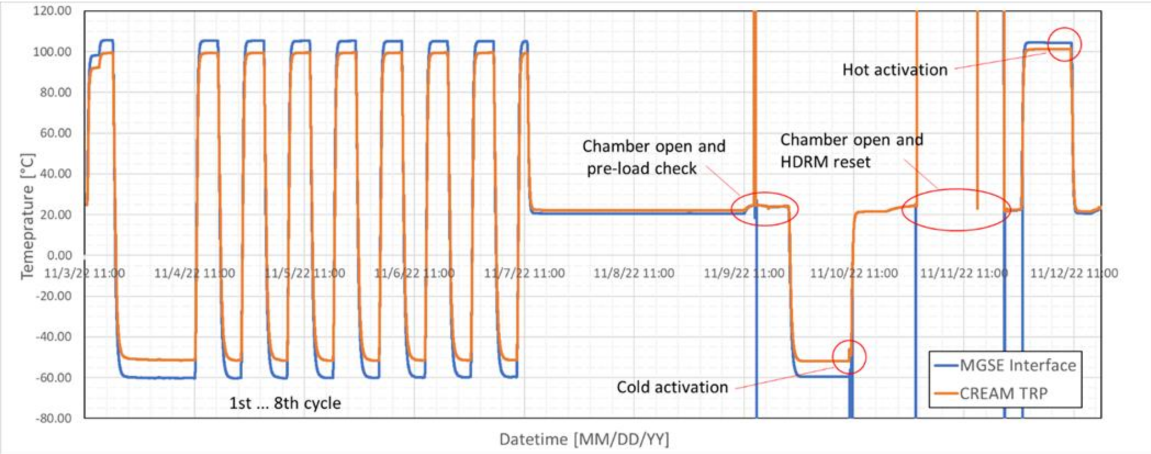

Figure 12 Temperature record of the CREAM HDRM thermal cycling test

temperature cycled between −50°C and +100°C. After eight cycles, the pre-load was checked under in ambient condition, and then the release operations were executed under −50°C and +100°C afterwards. Figure 12 shows the recorded temperatures during the temperature cycling and the release operations. For both temperature conditions, the release operations were successfully executed.

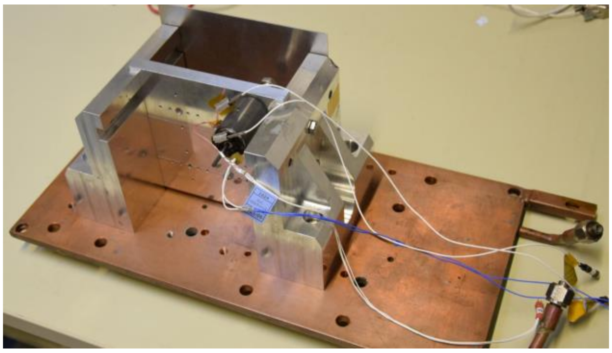

Figure 11 CREAM and MGSE mounted on the cold plate for the thermal cycling

6. INDUSTRILIZATION

The CREAM HDRM technology will be industrialized by DCUBED (Deployables Cubed GmbH). The collaboration with DCUBED will allow for a fast commercialisation of the CREAM HDRM technology to become a COTS HDRM product. Any interested reader can request further details by contacting the authors or DCUBED directly by mail (team@dcubed-space.com).

7. CONCLUSION AND OUTLOOK

This paper did introduce the new CREAM HDRM technology. The currently available designs for the 1.5 kN engineering and qualification models have a good volume-to-preload and mass-to-preload ratio, which makes the design capable to split spool HDRMs in this field. The actuation time was measured at ambient to be approx. 2 s. Although this is significantly longer as on split spool devices, it is still very convenient to be used on satellite missions. Mechanical-dynamical and thermal-vacuum testing did not reveal any large drawback within the design. Ground testing showed very easy handling of the HDRMs in terms of resetting and preloading. The upcoming weeks will be used to start the qualification program, which covers:

- Long-term preloading Test
- Life Test
- Mechanical-Dynamical Vibration
- Thermal-Vacuum Cycling and Activation
- Release Shock Measurements
- Shock Tests

These tests will conclude the qualification of the 1.5 kN HDRM at DLR.
A medium-sized 5 kN CREAM HDRM is currently in integration and will undergo same qualification program. This HDRM is a scaled version of the introduced design.

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