Development and qualification of a High-Temperature Shape Memory Alloys based Actuator for Hold Down and Release Mechanisms (HDRM)

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ABSTRACT

Many space applications such as satellite solar panels deployment require a hold down and release device. However, with the emergence of Newspace and the reduction of satellite's sizes, prime manufacturers need increasingly smaller mechanisms. [1]

Shape Memory Alloys (SMA) are often proposed as a non-explosive solution to provide a simple, safe, and reliable means of anchoring spacecraft appendages during launch. SMA can be triggered by heating to return to its initial shape. Such devices based on the more well-known SMA, NiTi, were developed and used, but were limited by their low actuation temperature (about 100°C).

CN-250X (Copper-Aluminium-Nickel single crystal) alloy [2] is an SMA that shows two desirable properties compared to NiTi for space applications. On one hand, the actuation temperature of this copper based SMA can be set between -200 and 250°C; typically, it can be adjusted around 155°C, meaning a margin of 30°C compared to the maximum temperature encountered in Orbit. On the other hand, CN-250X provides higher elongation during its martensitic transformation than NiTi, reducing the volume and weight of the actuator [3].

This paper presents the development and qualification of an HDRM range developed by Nimesis Technology and CNES called Triggy and based on the CN-250X alloys. 16 Triggy are proposed (8 sizes and 2 electrical interfaces) to break a mechanical link by providing fracture of a fastener.

INTRODUCTION

In 2020, Nimesis and CNES finalised the full specification and definition and are now focusing on the qualification of this range of actuators. The qualification process aims to demonstrate and validate the design of the Triggy actuators and the use of CN-250X as an approved material for space through:

- Functional tests, in the air and under vacuum, at low and high temperature
- Thermal and functional cycling tests
- Vibration tests
- Generated Shock measurement

Several satellites and rovers are already aiming to use Triggy as a baseline mechanism.

The paper will present the selection and design phase of the actuator family. Subjects like thermal insulation, heating, mechanical behaviour, material selection are all points that needed to be consolidated before the qualification phase. It will also present the validation of some technologies and the qualification plan for the actuator.

GENERAL DESCRIPTION

Triggy is a range of smart actuators for HDRM. Dedicated to space applications, this high-tech product is adapted from largest to smallest satellites as well as other spacecrafts – as rovers for example.

Figure 1 : Triggy range

Through its simple configuration and use, Triggy is very reliable. Indeed, this Launch Lock Device (LLD) is mainly made of a compressed SMA component, a pre-notched stainless-steel bolt – or fastener, a heater and temperature sensors. The high-power density heater allows the shape recovery of the SMA when heated, with a 155°±5°C transition temperature. As a result, the fastener stretches until it fails at the notch, providing controlled breakage and so enabling the release of the mechanism.

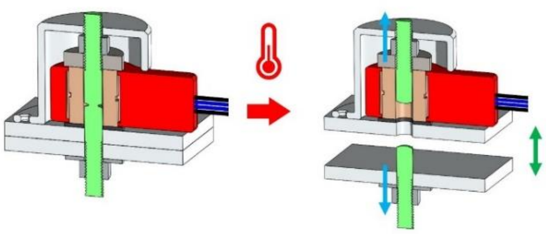


Figure 2: principle of Triggy actuation

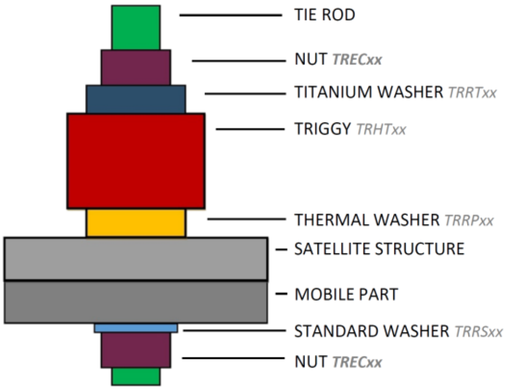
The shape memory alloy used for Triggy is a single crystal copper-aluminium-nickel called CN-250X, a high performance SMA capable of providing 8% strain at high temperatures, which allows it to adapt to different space environments (deep space missions, for example).

The SMA actuator is reusable after cooling and can be mechanically reconditioned to its armed length, thanks to a reset tool also developed by Nimesis (refer to part "accessories and equipment")

	TRHT02	TRHT03	TRHT04	TRHT05	TRHT06	TRHT08	TRHT10	TRHT12
Material	CN-250X	CN-250X	CN-250X	CN-250X	CN-250X	CN-250X	CN-250X	CN-250X
Screw size	M2	M3	M4	M5	M6	M8	M10	M12
Maximum axial preload (N)	1350	3376	5848	9572	13503	24786	39468	57551
Fracture load (N)	1874	4689	8122	13294	18754	34425	54817	79932
Nominal power (W)	6,5	12,0	21,8	36,1	33,4	61,9	101,5	150,7
Outer diameter (mm)	10,0	15,4	20,0	24,0	28,0	34,4	40,4	47,8
Elongation (mm)	0,82	0,90	1,13	1,39	1,71	2,20	2,74	3,32
Armed length (mm)	9,22	10,10	12,67	15,51	19,14	24,65	30,66	37,18
Fired length (mm)	10,04	11,00	13,80	16,90	20,85	26,85	33,40	40,50
Weight (g)	3,5	9	15	26	45	90	170	300

Figure 3 : Triggy data sheet and specification [6]

Figure 4: a Triggy HT04



Technical specifications

Triggy comes in 8 bolt sizes ranging from M2 to M12 and can sustain up to 57kN. Then, each size is available in 2 electrical models with different voltage ranges. The complete range is therefore wide enough to suit all sizes of satellites and other spacecrafts. This is strong advantage for the last generation satellites - from "New Space" - which are more and more miniaturized.

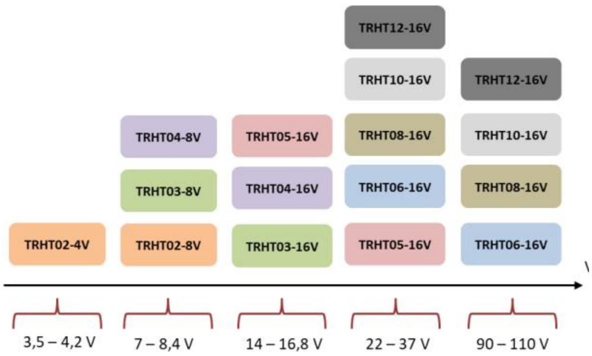


Figure 5: Available voltage for each Triggy size

Typical integration

Triggy integration comes with several components: Triggy, thermal insulating washer, titanium washer, standard washer and nuts. Typical integration is shown below.

Shape Memory Alloy technology description

Shape memory alloys (SMAs) are recognised as reliable and efficient materials for actuators' design. The major drawback of these shape memory actuators is the triggering temperature which is below 100°C with standard Ni-Ti alloys. Nimesis' CN-250X exhibits a transformation temperature which can be adjusted between -200°C and +250° and is available in round cross-section with a diameter of 0.5 mm to 35 mm. The state of the art and detailed characterisation work carried out for several recent CNES R&T programmes have demonstrated that Cu-Al-Ni single crystal wire is a very good candidate for space applications that require triggering temperatures between 100°C and 200°C.

A dedicated alloy has been manufactured during this program. The casting shows transformations temperature at 155°C ± 5°C. After casting, the alloy is transformed into semi-finished products and then NIMESIS performs its patented single crystallization process to obtain a high performances SMA component.

Heating device

The heating required for the SMA to reach its actuation temperature is provided by two heaters - one main and one redundant manufactured by a space qualified heaters supplier. These heaters are based on the flight-proven All-Polyimide technology. In order to reach the actuation temperature (over 155°C) from the space environment (-120°C to +120°C), the required power density was set at a level above the values usually encountered in the space industry and proposed by the ECSS standards (0.5W/m2). The ECSS standard is used for thermal control with long duration and low temperature (<120°C). It means that heaters need to be used with small power density to ensure its lifecycle during the mission. For Triggy, heaters will be used only once, and need to heat the SMA component as fast as possible. In fact, it needs a large amount of power for a very short time (less than 10min) to limit the energy consumption. The all-Polyimide technology allows to manufacture flexible heaters, able to follow the radial deformation of the SMA.

However, this technology is limited by the degradation of Polyimide that occurs at 300°C. Many tests have been realised on heaters after actuation with incremental power density and thermal ageing to ensure the validity of the technology. During ageing, overheating of the material was controlled with a thermal camera and heaters were controlled with a binocular magnifier after each test.

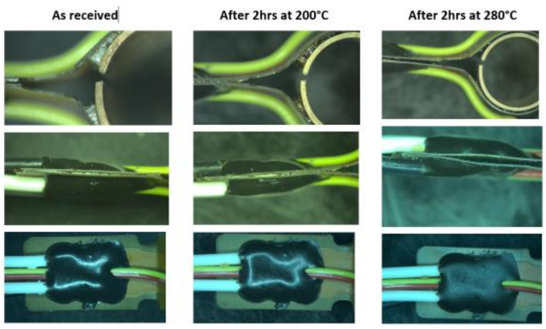


Figure 6: visual inspections of All-Polyimide heaters after ageing

The ageing test set the temperature limit at 280°C (for a 2-hour exposure). At this temperature, the heating element shows no damage, but the glue used to fix the heating element to the ring blackens and cracks appear on the welding of the thermal probes.

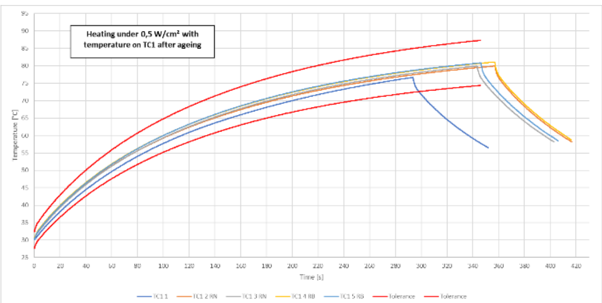


Figure 7: Heating under 0,5 W/cm² with temperature on TC1 after ageing

No damage nor overheating of the component have been seen until 30 W/cm2 and no variation of electrical properties have been noticed on heaters until 22 W/cm2. With a safety coefficient of 2, a limit was set at 11W/cm2 for the power density. The heater can be used up to 11 W/cm2 without counter-indication in a short period (less than 10min).

To ensure a good thermal contact, heaters are mounted on a CuBe ring (a flexible and good thermal conductor metal). The width of the rings has been optimized through numerical simulation to allow a contact with the SMA during its shape recovery without yielding.

Definition and manufacturing of the Tie rods

Tie rods are proposed in stainless steel 15-5PH H900. This material is commercially available at a reasonable price and provides high mechanical performances. Coefficient of thermal expansion is also comparable to the CN-250X, so it allows to reduce thermoelastic effect. It has been decided to use it for manufacturing of tie rods, nuts and washer. Numerical simulations have been made to verify that thread will not be damaged under the fracture load at actuation.

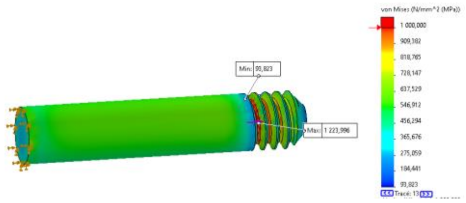
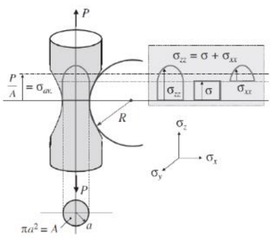


Figure 8: stress repartition on the threaded part of a Tie Rod

The notch allows to localize the breakage of the Tie Rod and to maximize the fracture load. The objective is to have the highest preload with each fastener's size. This increase depends on the shape of the notch and is described as the Bridgeman effect [5].



$$\sigma = \frac{\sigma_{av.}}{\left(1+\frac{2R}{a}\right)\log\left(1+\frac{a}{2R}\right)}$$

Figure 9: detail of the notch

This formula calculates the stress concentration before the fracture. And it will depend on the notch radius. When radius is small, it means that stress concentration is high. In our case, the notch allows to increase the stress concentration (and so the preload and fracture load) by a factor of 1,84.

Tie rods are not manufactured internally but by selected external providers. As the tolerance is very low (+0 / -0.05mm) and the material is hard to machine, the manufacturing of the notch requires a good know how and experience. Several providers were tested with very large quantities of tie-rods. The manufacturing tolerance is directly linked to the mechanical margin. Dimensions are then fully checked with a profile projector to eliminate all risks of non-actuation due to higher breakage load.

PRELIMINARY DESIGN AND TESTING

Heating simulations

To design and fix the heaters performance, a thermal model was implemented through FlowSimulation. This software uses a Finite Element model (FEM). The model is based on a generic Triggy assembly. The assembly locked by the Triggy is represented through a large cylindrical plate in Aluminum. This plate simulates the thermal dissipation generated by the assembly. An insulating washer, made of high-performance thermoplastic, has been inserted between the Triggy and the plate.

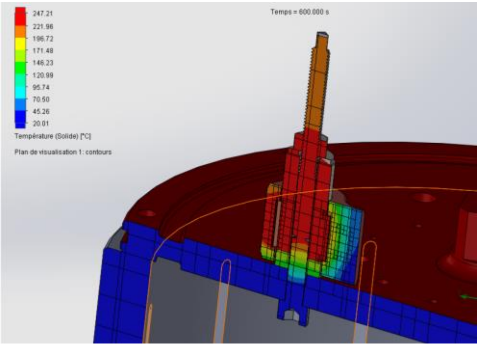
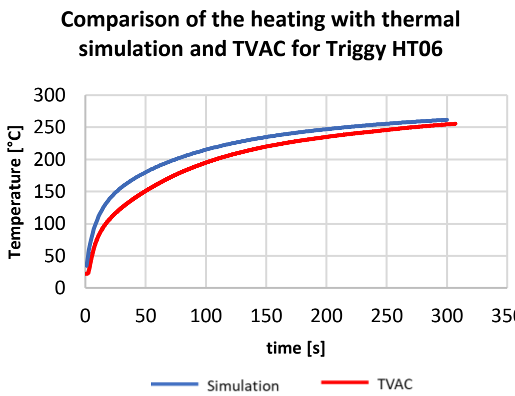


Figure 10: thermal model of Triggys at actuation

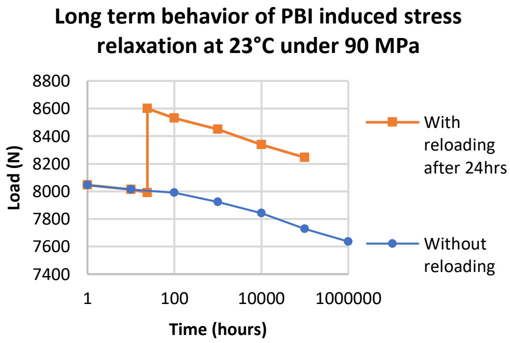
Actuations of Triggys have already been performed under vacuum (TVAC) at -120°C, 23°C and 120°C within the CNES facilities in 2019. The heating of the actuator has been monitored and compared to the numerical simulations.



Insulating material

An insulating washer allows to reduce the thermal dissipation between the Triggy and the assembly during the heating. It allows the Triggy to be actuated between -120°C and +120°C with a small power consumption. It appears that any kind of metallic material can't be used because thermal conduction is too high. We decided to use a thermoplastic, PBI (Polybenzimidazole) was chosen among other thermoplastics for its good stiffness at high temperature and its lows creep rate.

Numerical analysis and creep tests showed that at 90 MPa and at 150°C, the preload would decrease by up to 30% after 10 years. It was shown that applying again the preload 24hrs after the integration allows to reduce this effect at less than 10%. Curve below shows the creep curve of a washer loaded at 8600 N with and without preloading after 24 hours.



Procedure for preloading a fastener with PBI washer is defined as below:

1. Loading to nominal preload
2. Waiting for 24 hours
3. Loading to nominal preload

Coating

A silicon coating around the actuator allows to protect heaters from mechanical stress and any kind of pollution. It also gives the heaters the possibility to have a higher power density because of thermal contact with it, it improves the thermal homogeneity of heaters. The material is Nusil CV17-2500, a space qualified silicon with very low outgassing rate (less than 0.1% CVCM and 0.01% TML). DSC (Differential Scanning Calorimetry) were performed by CNES on the material and concluded that Nusil shows no specific change of property after glass transition at -113°C.

Margins

The design of an SMA actuator implies the definition of its thermal margins along with mechanical margins. In fact, the maximum temperature allowed on the SMA depends on its maximal stress. The stress on the SMA is computed to reach the tensile stress of the Tie Rod. 10% of dispersion and 25% of safety margin are considered, leading to 17% of residual margin with the stress that the SMA can allow. This margin takes into account all tolerances, safety coefficient, thermoelastic behavior and ECSS factor.

Figure 11: definition of mechanical margins

The nominal actuation temperature is defined with 30°C margins toward the environment (120°C). The highest temperature allowed by the SMA is defined by the maximum tensile stress on the Tie Rod, leading to heat the SMA at 188°C. Considering the temperature probes uncertainities, the gradient of temperature between the SMA and the sensor and the heaters and the 5s of latency on the heater after the actuation, 50°C of residual margins are saved toward the maximum temperature of Polyimide (300°C for short term exposure).

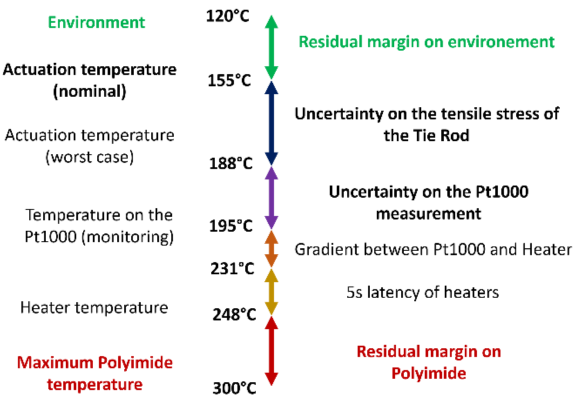


Figure 12: definition of thermal margins

Finally, the budget of displacements is made to assess the performance of Triggys. In fact, the SMA shall provide enough displacement to break the Tie Rod and to compensate the thermal and mechanical deformations of all other components (washers, nuts,…and hold downed assembly).

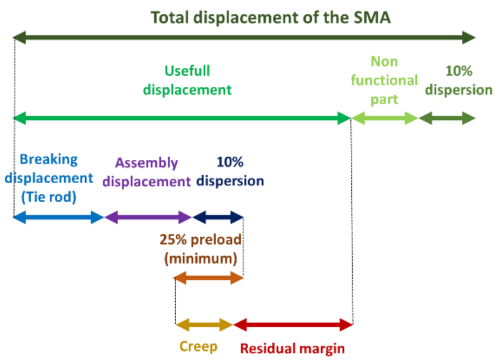


Figure 13: budget of displacement

The residual margin in term of displacements depends on the size of the Triggy and varies between 25 and 35%. This margin allows to consider the displacement lost in the assembly to hold down as well as thermal dilatations.

The consideration of mechanical and thermal margins results in a reliable and robust actuator.

OPERATION MODES

Triggy has two operational modes: In nominal condition, the electrical power is applied on the main heater, and on the redundant one in case of degraded mode. If both sensors are nominal, the heating is performed until the maximum temperature (with margins) is reached on both sensors. If only one sensor is functional, the power is applied until this sensor reaches the triggering temperature. If any sensors are functional, then the power is applied during the maximum duration provided by Nimesis' or user's numerical simulations or when appendage is released.

QUALIFICATION TEST CAMPAIGN

Qualification objective is to demonstrate that the actuator is operational and complies with the product requirements including margins. As already presented, the Triggy range is composed of 16 variants: 8 geometrical sizes proposed in two electrical interfaces. In total, 16 Triggys are to be qualified. The qualification is declined in two sequences, because of the number of variants.

In a first time, a complete qualification will be performed on the 8 variants with the highest commercial need. The other variants will be qualified in a second time. In fact, only electrical characteristics will evolve but it has been decided to perform a complete qualification on all variants to demonstrate the robustness of Triggy actuators.

In the frame of the qualification, 5 models will be tested for each variant (geometrical & electrical):

- A "nominal case model" QM1 for vibration, shock, thermal cycling and vacuum heating with nominal power
- A "worst hot case model" QM2 for vibration, shock, thermal cycling and vacuum heating with maximal power at high temperature
- A "worst cold case model" QM3 for vibration, shock, thermal cycling and vacuum heating with minimal power at low temperature
- A "long term storage model" QM4
- A "reliability model" EQM5 for hardened tests and with thermocouples for advanced thermal analysis refine.

The process will last 3 months for the first phase and 3 months for the second. The 8 first variants will be qualified in Q4 2021 and the other in Q2 2022. The qualification will involve 112 Triggys and 2624 tie rods.

The qualification logic is summed up like this:

	QM1 ROOM TEMPERATURE	QM2 HOT CASE	QM3 COLD CASE	QM4 STORAGE	EQM5 REALIABILITY
ACCEPTANCE	X	X	X	X	X
LIFE DURATION (PHASE 1)	X	X	X	X	X
VERIFICATIONS AND ASSEMBLY	X	X	X	X	X
VIBRATIONS AND SHOCKS	X	X	X	X	
THERMAL CYCLING	X	X	X	X	
ACTUATION UNDER VACUUM	X +20°C	X +120°C	X -120°C	X	
LIFE DURATION (PHASE 2)		X	X		
EXPERTISE	X	X	X	X	X
RELIABILITY					X

Tableau 1: qualification logic for each model

Acceptance

Acceptance test will be performed for each QM and later on each flight models. It will consist of electrical, dimensional, heating (with both main and redundant heaters), conditioning and actuation tests.

Life duration (Phase 1)

Triggys will be actuated at room temperature and under normal atmosphere with different preloads and power. Exported shocks will also be measured.

Verification and assembly

The isolating and electrical resistances will be measured. Dimensional and visual inspections will be performed as well as assemblies with the tensioner tool.

Mechanical environment

Preloaded QM will be subjected to qualification levels of sinusoidal and random vibration as described by ECSS standards. Vibration test will be performed by an external provider. The actuator will endure random vibrations and sinusoidal vibrations at the following levels:

Frequencies	Amplitude
20 - 50 Hz	+3 dB/oct
50 - 600 Hz	2 g2/Hz
600 - 2000 Hz	-3 dB/oct

Preloaded QM will be subjected three different shock tests in each of the three axes separately since g-loads do no act simultaneously to all three axes.

Exported shock

Measurements of exported shock at actuation have already been performed on some variants of Triggys such as HT03, HT04 and HT06. The shock is important, but still lower than with pyrotechnic device. [4]. Nimesis develops solutions to reduce the shock, such as a damping casing.

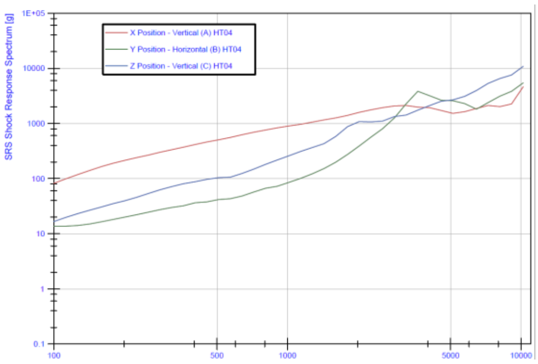


Figure 14: shock test result on HT04

Thermal cycling

Thermal cycling tests aims at qualifying the preloaded actuator for thermal environment before actuation. 8 cycles of 320min will be performed for each Triggy between -120°C and +120°C under vacuum (10^{-6} mbar).

Thermal Vacuum test

Actuation will then be performed at -120°C, 23°C and +120°C under vacuum. The heating will later be analyzed when Triggys will be back to atmosphere. The heating dynamic will be analyzed in TVAC (10^{-6} mbar) and compared to the numerical simulations as well as the retention of the preload.

Life duration phase 2

It is required 10 ground and 1 in-orbit functioning. Applying ECSS factors (4 for ground functioning and 10 for in orbit ones), at least 50 actuations will be performed.

The emitted shocks will also be measured

Expertise

An expertise will be performed on the 16 variants to assess the degradation of Triggys with thermo-mechanical cycling.

Reliability

Hardened test will be performed to assess the margins took during the design process (dimensions of the notch, grubbing of the cables, thermal balance).

ACCESSORIES AND EQUIPMENTS

Mechanical Ground system equipment (MGSE)

To target the nominal performance of Triggy, two MGSE are developed by Nimesis Technology to prepare and install the actuator on the system. The reset tool allows to arm the Triggy. This is a portable hydraulic press that allows to compress the Triggy at the load required to reach the armed length. The respect of the compression load given by Nimesis is crucial for the good behavior of the Triggys. In fact, with a lower load, the Triggy will not reach the desired displacement and with a higher load, the transformation points of the SMA will increase and so will increase the actuation temperature.

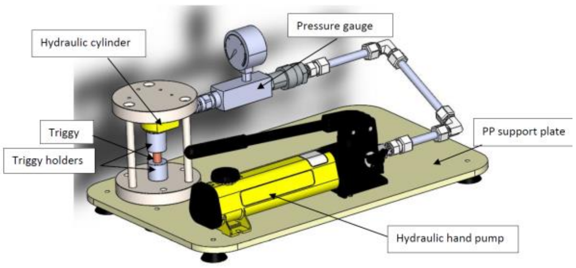


Figure 15: reset tool

A tensioner tool was also developed to meet the highest preload on the Tie-rod. In fact, when then preload is applied through torque, a high amount of the load is lost in shear-stress. A pure axial load is achievable through the tensioner tool that converts a Torque to an axial load thanks to a flattened shaft. The load is monitored with a load cell and its display. Tests performed internally showed that the preload achievable with the tensioner tool is 2 to 4 times higher than with torque, and with limited dispersion (the tensioner tool does not require specific lubrication).

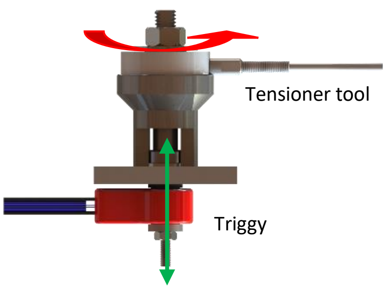


Figure 16: tensioner tool with a Triggy assembly

Load measurement

The measurement of the load in the Tie-rod is necessary for the qualification, mainly to monitor loss of preload after thermal cycling, ageing, storage, shocks or vibrations. Standard load cells proposed by aerospace manufacturer inserted in the assembly will be used for test at room temperature. At low/high temperature and under vacuum, Tie Rods equipped with strain gauges will be used and could be later proposed as a standard solution for flight models.

Test bench

The test bench is a mechanical assembly used to test the entire Triggy range. It will be used for vibrations, shock, thermal ageing, and thermal cycling tests. This bench is equipped with 8 slots for M2 to M12 Triggy. It is used to contain the components which are expelled when the tie rod breaks. It is equipped with 3 accelerometers (one per X, Y, Z axis). The acquisition is made at 1,000,000 Hz and is triggered when the tie rod broke for 100ms. 5 test benches will be manufactured, one for each reference of QM (QM1 to QM5).

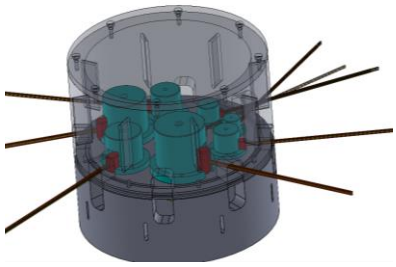


Figure 17: test bench of Triggys for qualification tests

LESSONS LEARNT

Many lessons were learnt during the development and qualification preparation of the Triggy family. A few key lessons learned are highlighted below:

- In terms of measurement, the means discussed at the beginning of the development, such as load cells, were not compatible with the constraints of environmental tests (thermal, vibrations and shocks). New solutions, such as the instrumentation of Tie rods with strain gauges have been implemented and will be used during the qualification campaigns.
  Such instrumented tie rod will be available for purchase as FM.
- Mechanical and thermal margins were studied with a lot of effort to ensure that, in any case, Triggy will Trigger nominally.
- All-Polyimide heaters are able of short terms operation at high temperature and at high density power with no significant degradation. It allows the All-Polyimide heaters to be used at a higher power density than indicated in ECSS standard when the application needs a very short-term use.

- Supporting a qualification test campaign with multiple variants of a product requires significant effort to verify and validate technical requirements. The test campaign induces a high number of tests of multiple components.

SUMMARY AND OUTLOOK

Technological testing on engineering models and separated subsystems of the actuators allowed to refine the design of the Triggy family in time for its qualifications.

At the time of writing, all QMs, MGSEs, accessories (Tie rods, washers, nuts), instrumentations are in process of manufacturing for a start of the qualification campaign in September 2021. The qualification review of the 8 first variants (HTXXXXX) is planned in December 2021. The 8 last ones qualification review is planned in march 2022.

ACKNOWLEDGMENTS

Triggy is developed as a cooperative effort between Nimesis Technology and the CNES (Centre National d'Etudes Spatiales)

REFERENCES

[1] California Polytechnic State University. Cubesat design specification rev. 13. Technical report, 2014

[2] Cu-Al-Ni Shape Memory Single Crystal Wires With High Transformation Temperature, ESMATS Poster 2015

[3] Development and Testing of a High-Temperature Shape Memory Actuator Using CN-250X for Hold Down and Release Mechanisms (HRM), ESMATS paper 2017 0026fouche

[4] Busch D. J, Purdy W. E, Johnson A. David, devlopment of a non explosive release device for aerospace application, 26thAerospace Mechanism Symposium

[5] Studies in Large Plastic Flow and Fracture, Mc Graw-Hill.New York (1952), P.W. BRIDGMAN

[6] Data_sheet-NIMESIS-Triggy-2021-V4, Nimesis Technology, 4, Rue des Artisans 57245 Mécleuves, France