ESA CLEANSAT_SMA Dismantlement Mechanisms

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ABSTRACT

Preliminary analyses at ESA have shown that space objects in LEO with masses above 500 kg might already imply an on-ground casualty risk higher than 1E-4 in case of uncontrolled re-entry. Compliance to this casualty risk requirement may be achieved through controlled re-entry, but this solution has a major impact at system level, sometimes requiring the full re-design of the spacecraft and may involve switching to a completely different launcher performance (consequently a significant mission cost impact).

This option may be avoided with achievement of compliant ablation (demise) of the spacecraft upon uncontrolled atmospheric re-entry. The so-called Design-for-Demise discipline (D4D) is a highly multidisciplinary approach that can bring significant benefits in the future missions in the medium to long term.

ESA created in 2012 the "Cleanspace" initiative and team to promote actions on green aspects and debris remediation. Recently ALTRAN was involved inside THALES ALENIA Space consortium in those ESA activities on S/C D4D techniques and proposed several D4D concepts. This ESA D4D study had the objective to find D4D solutions for the Sentinel-1 study case (around 2 tons). This objective were about to be theoretically achieved.

The outcomes of those D4D studies performed in parallel at level of 3 LSI (Large Single Integrator) used mainly ESA Sentinels S/C as study cases. Those studies all demonstrated that S/C dismantlement (controlled and earlier to natural break-up) has a major benefit in reduction of S/C Debris Casualty Area (DCA). Then this technique has to be considered with high priority in a global approach for D4D improvement.

The proposed study CLEANSAT Building Block 10 (Shape Memory Alloys (SMA) Dismantlement Mechanisms identified by ALTRAN and NIMESIS) has investigated several technological devices and SMA material options and their suitability to be implemented in LEO satellite H/W of main European LSI for dismantlement during atmospheric re-entry

1   OBJECTIVES

This study has mainly inspired ALTRAN Research during ESA Design for Demise (D4D) activity for THALES Consortium [11] concluded in early 2016 [17] [18].

Nevertheless this problematic of S/C dismantlement was initially identified at ESA CDF MICRA Webcast open to industry in late 2013 [10]. The benefit of an early and controlled S/C dismantlement was already clearly identified. During those webcasts open to industry, ALTRAN proposed several concepts including the AltranSat V2 introducing structural blocks release by mechanisms triggered by re-entry temperature.

This technique was clearly confirmed at end of ESA D4D Activity by TAS & ADS consortium even if elements such as propellant tanks or reaction wheels are design to demise, the late exposure of those elements in aerothermal flux could still jeopardize their demise.

So, ALTRAN investigated several technologies

- Pyro-cut & Thermo activation
- SMA activation ,
- Glue sublimation on already existing H/W or dedicated glued path for dismantlement
- Easy Demise elements

After preliminary assessment, the attention was concentred on dedicated release mechanisms that can be triggered at SMA higher temperature (as proposed by NIMESIS)

The main problematic points to be investigated on this study **:**

- Clarification of S/C thermal environment in S/C early reentry (External –Internal T°)
- Clarification of S/C Dismantlement needs (applicative study cases – preload/rupture)
- Clarification of SMA capabilities : Stress range / Safe – Triggering T°
- Engineering of dedicated innovative Concept to fulfil LSI S/C dismantlement needs

S/C re-entry environmental conditions considered by ALTRAN at the beginning of the study were:

>150 km (Solar Flux but Aerothermal flux negligible)
No debris or release allowed
(25years max atmospheric decay period)
- ⇨ Safe temperature wrt to SMA transition
- ⇨ Max External T° assumed 120-150°C (TBC)
- ⇨ Max Internal T° assumed 75-100°C (TBC)

150-120km (Aerothermal Flux but no Re-entry)
Start of SMA heating & transition phase
(early re-entry period, several orbits and hours)
- ⇨ Max External T° assumed 250-350°C (TBC)
- ⇨ Max Internal T° assumed 90-120°C (TBC)

120-100km (Aerothermal flux & Re-entry)
Range of intended External release
(the highest altitude , the better)
- ⇨ Min External T° assumed 0-50-100° (TBC)
- ⇨ Min Internal T° assumed 0-50°C (TBC)

100-80km (Reentry before S/C Break-up)
Range of intended internal Release
(the highest altitude , the better)
- ⇨ Min External T° assumed >100°C (TBC)
- ⇨ Min Internal T° assumed >100°C (TBC)

2 APPLICATIONS

2.1 Release External Panels

The early release of external S/C panels is obviously a global benefit for S/C demise
Different study cases will be investigated through a trade-off to determine what is the most suitable solution for panel release with a mix of the proposed concepts.
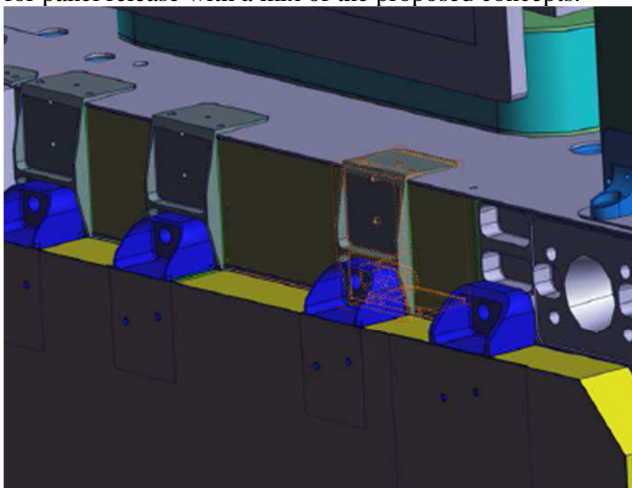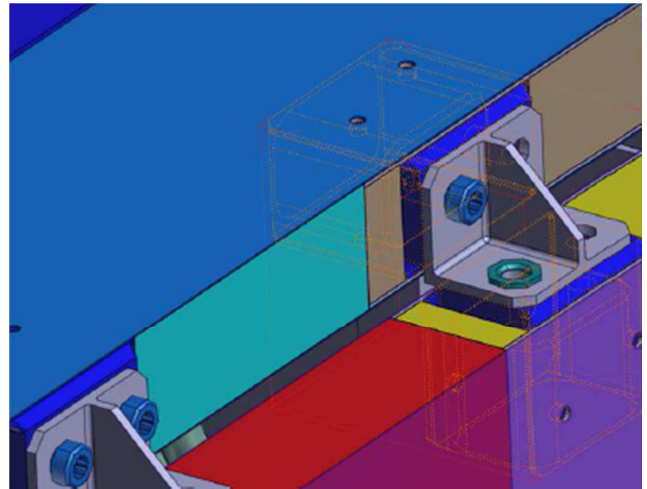

Figure 1. Panel junction with deck (end inserts) [18]

Figure 2. Panels junction with end & bobbin inserts [18]

3-4 Study Cases proposed by ESA and LSI have been investigated
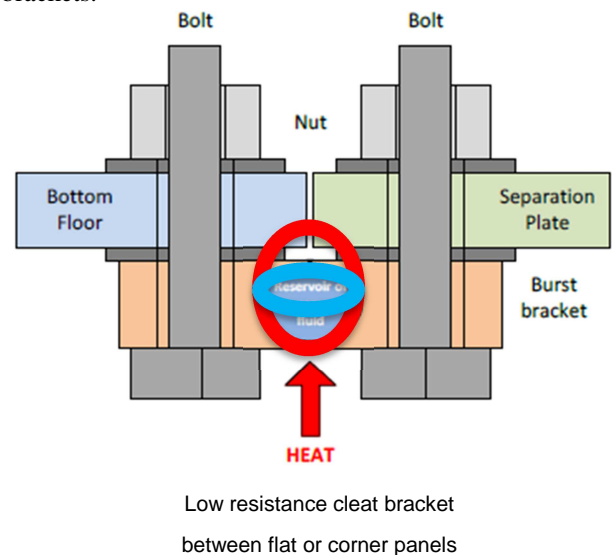Those solutions are all based on flat cleats or junction brackets.

Low resistance cleat bracket

between flat or corner panels

Figure 3. Cleat junction releasing in temperature [17]

- ➤ **Study case 1**: Cleat / "Bobbin" inserts / Internal access

- ➤ **Study case 2:** Cleat / Mix Bobbin & End Panel inserts / External access

- ➤ **Study case 3:**Cleat / End Panel inserts / External access

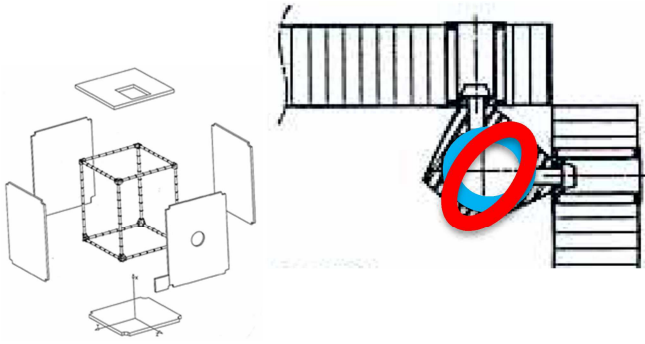- ➤ **Study case 4:** Tubular Frames / Screwed panel

Figure 4: Structural Bar cut in temperature

In this case, the external panels are maintained on a tubular frame bars and end brackets

The intention is to investigate how the structural frame can be dismantled by an equivalent pyro-cut.

The bars can be dismantled by end SMA sleeve (as presented in a other concept) or direct SMA brackets

But in order to release panel / panel the tubes have to be cut in longitudinal direction

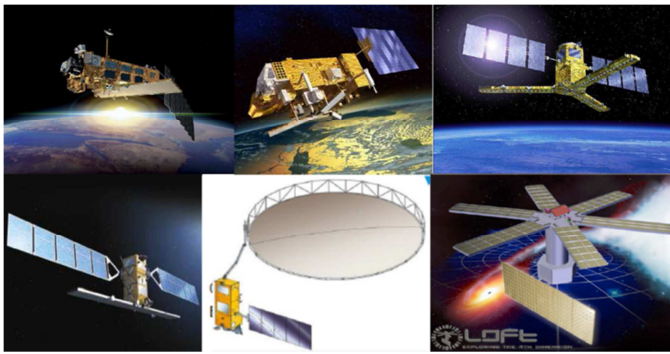## 2.2   Release External Appendages

Figure 5: ESA Satellite with External appendages

As investigated in the past on ESA D4D S/C activity [17]]18], it has been demonstrated that early release of external appendages of a re-entering spacecraft has a global demise benefit for the rest of the spacecraft .

A lot of LEO S/C have external appendage for scientific missions:

ENVISAT, ERS, METOP, SMOS, COSMO-SKYMED, Sentinel-1, LOFT, BIOMASS

Releasing those appendages implies to clarify what are the structural interfaces used for those appendages. If most of the elements are based on deployable (and lightweight) mechanisms, they also used standards interfaces such as screwed interfaces (compatible with frangibolts) but also some specific interfaces such as Yokes , bars and booms (pretty compatible with SMA Sleeve concepts with a ratio of one sleeve versus 4 frangibolts)
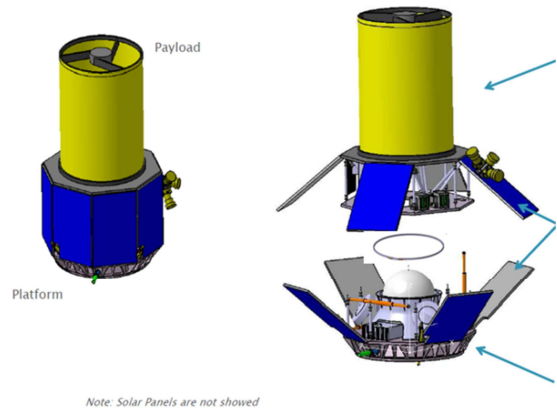
2.3   Release S/C Modules

Figure 6: ALTRANSat Concept V2

As investigated in the past on ESA D4D S/C activity [17] [18], it has been demonstrated that early dismantlement of S/C modules: P/L and P/F etc… of a re-entering spacecraft has a global benefit for the rest of the spacecraft demise.

Several devices have been investigated since ESA Micra Webcast on D4D S/C by ALTRAN. Those concepts were inserted in the ALTRANSat V2 focusing early release/demise of external panels and on dismantlement capability of modules (see above).

Main technological devices investigated were about:

- Glued I.Fs or glued path
    - released at hot temperature
- Upper deck and tube junction with clamp band
    - release by one single Frangibolt
- Struts assembly between modules

    - Release via frangibolts , inserts, sleeves ,

Main concept suitable for this application was identified to use structural struts. This element gives advantage to concentrate the loads in segregation points and then reduce the release interfaces. Several options can be proposed for a release at strut level: Frangible joints or release panel inserts at interfaces,   release Sleeve , adapted mechanism at interface :
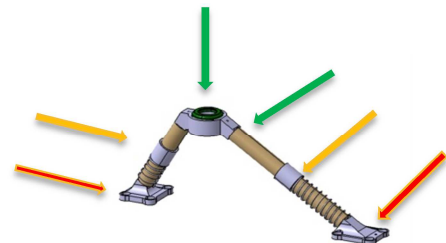

Figure 7: Strut release options (color code)

3 REQUIREMENTS

Buildi ng	Building Block Name				P
BB-10	Early structure break-up				PC
	Requi reme nt ID	Requirement topic	Requirement text	Comments/Justification	C/ PC/ NC
BB10-ASD-I-01	BB10-TAS-I-03	BB06-OHB-008	Performance	Actuation Temperature at device level **Internal Elements : T>90-120°C (TBC)** **External Elements : T>150°C**		C
		BB06-OHB-009	Performance - Activation Time	For active heating the time between activation and separation shall be between 10min (TBC) and 30min		C
		BB06-OHB-010	Performance - Operating Temperature	The operating temperature range shall be **-40°C to + 90°C (internal)** **-120°C to + 120°C (external)**		C
		BB06-OHB-013	Reliability	The reliability of the succesful break up of the satellite structure shall be >95% (TBC) Intention at device at level shall be X100 more reliable Goal=1E-4 per device (failure in proper actuation & release)	**Translated in Reliabilty per device = 1E-4**	TBC
		BB06-OHB-	Lifetime On-Ground	On ground storage lifetime shall be 10years.		C
	BB10-TAS-I-	BB06-OHB-	Lifetime In-Orbit	Lifetime on-orbit of 15 years.		C
		BB06-OHB-016	Environment - Thermal	The thermal environment on-orbit shall not cause an unplanned activation of the SMA.		C
	BB10-TAS-I-07	BB06-OHB-017	Reliability (SDM)	Reliability <1E-3 against failure per device (unplanned activation from element)		TBC
		BB06-OHB-018	Performance	The break-up of the satellite structure shall occur at an altitude between 90 km and 150 km (TBC). Converted in maximum actuation temperature : **T= 150°C (internal) 200 °C (external)**	Note: The altitude is specified in order to be not dependent on the satellite configuration	C
		BB06-OHB-022	SDM - Particles	Actuating the mechanism shall not release particles larger 1 mm (of its largest dimension)		C
	BB10-TAS-I-05		Demisability	The mechanism itself shall be demisable		C

Figure 8: LSI requirements

4 CONCEPTS DESIGN

4.1 Concept 1: SMA Washers / Frangible Screws

4.1.1 TINI Aerospace products

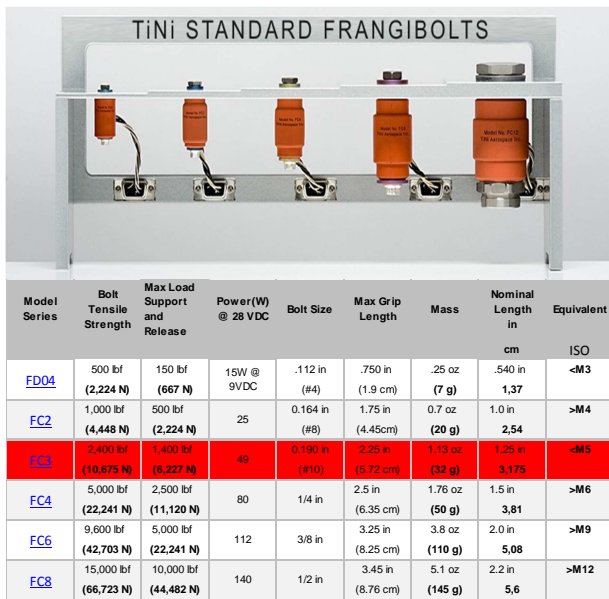They are considered as good design drivers with the intention to provide ISO M devices for European space industry.

Model Series	Bolt Tensile Strength	Max Load Support and Release	Power(W) @ 28 VDC	Bolt Size	Max Grip Length	Mass	Nominal Length in cm	Equivalent ISO
FD04	500 lbf (2,224 N)	150 lbf (667 N)	15W @ 9VDC	.112 in (#4)	.750 in (1.9 cm)	.25 oz (7 g)	.540 in 1,37	<M3
FC2	1,000 lbf (4,448 N)	500 lbf (2,224 N)	25	0.164 in (#8)	1.75 in (4.45cm)	0.7 oz (20 g)	1.0 in 2,54	>M4
FC3	2,400 lbf (10,675 N)	1,400 lbf (6,227 N)	49	0.190 in (#10)	2.25 in (5.72 cm)	1.13 oz (32 g)	1.25 in 3,175	<M5
FC4	5,000 lbf (22,241 N)	2,500 lbf (11,120 N)	80	1/4 in	2.5 in (6.35 cm)	1.76 oz (50 g)	1.5 in 3,81	>M6
FC6	9,600 lbf (42,703 N)	5,000 lbf (22,241 N)	112	3/8 in	3.25 in (8.25 cm)	3.8 oz (110 g)	2.0 in 5,08	>M9
FC8	15,000 lbf (66,723 N)	10,000 lbf (44,482 N)	140	1/2 in	3.45 in (8.76 cm)	5.1 oz (145 g)	2.2 in 5,6	>M12

Figure 9: TiNiAerospace product Catalog. [19]

4.1.2 NIMESIS products – Passive devices

The main mechanical data (load and tension) of NIMESIS alternative products were set within usual space standards, requirements and applications

- ECSS data are extracted Annex 1 of ECSS-E-HB-32-23A_16April2010
- LSI requirements mainly e from OHB
- TAS-F (internal standard IECA_0006 RSAT Screws)

A reminder of the geometry and the architecture of the SMA washer and the frangible screw is presented hereafter (Here the screw is replaced by a nut and bolt configuration)

Hereafter are reminded the

- "Frangibolts " stands for TiNiAerospace elements presented for comparison
- Triggering time are considered for active device (with embedded heaters)
  - Assumption made on NIMESIS thermal assumption are assumed with no electrical and thermal dissipation (very best case approach)
  -

Comparaison		M3	M4	M5	M6	M8	M10	M12
Frangibolt	Length (mm)	13,7	25,4	31,8	38,1		50,8	56,0
	Internal Diameter (mm)	3,2	4,6	5,2	6,7		9,9	13,1
	External diameter (mm)	5,6	7,5	10,2	14,0		18,2	25,4
	Thickness (mm)	1,2	1,5	2,5	3,6		4,1	6,2
	Weight (g)	1,5	4,6	12,5	28,9		59,5	134,4
	Triggering time (s)	20,0	32,0	30,0	35,0		60,0	72,0
ACT-NT Nimesis NiTi	Length (mm)	16,1	21,3	27,0	32,2	43,3	54,6	66,3
	Internal Diameter (mm)	3,2	4,3	5,3	6,4	8,4	10,5	13,0
	External diameter (mm)	6,4	8,5	10,8	12,9	17,3	21,8	26,5
	Thickness (mm)	1,6	2,1	2,8	3,2	4,5	5,7	6,8
	Weigth (g)	2,6	5,9	12,2	20,4	50,5	101,2	179,4
	Triggering time (s)	8,5	11,7	12,4	12,8	22,6	36,2	59,9
	Safety temperature (°C)	90	90	90	90	90	90	90
	Triggering temperature (°C)	139	139	139	139	139	139	139
ACT-HTCu Nimesis CuAlNi	Length (mm)	18	24	30	36	49	61	74
	Internal Diameter (mm)	3	4	5	6	8	11	13
	External diameter (mm)	7	10	12	14	19	24	30
	Thickness (mm)	2,0	2,6	3,4	4,0	5,5	7,0	8,3
	Weigth (g)	4,2	9,7	20,1	33,8	83,6	167,7	296,8
	Triggering time (s)	24,2	33,2	35,2	36,2	64,1	102,8	169,8
	Safety temperature (°C)	150	150	150	150	150	150	150
	Triggering temperature (°C)	224	224	224	224	224	224	224

Figure 10: NIMESIS geometrical and physical data of alternative products

2 different design are proposed to fit the 2 different alloy references (Each alloy option needs a specific design to cope with preload and rupture stress requirement)

The passive SMA washer design usually requires a (2D) external diameter (2 screw diameter)

The active SMA washer design requires a (2.5-3 D) external diameter (D=screw diameter)

The SMA washer diameter is significant to obtain an acceptable stress level

At Preload: the stress shall remain in SMA elastic domain **75-100 MPa Max**

At Rupture: the stress provided by heating (some MPa/°C) can achieve **150-250 MPa** and shall exceed screw rupture stress and tension.

The SMA length of the washer is relevant to exceed the extension at rupture on the restriction in the screw diameter (5% max extension offered by SMA in Compression transition has occurred).

It leads to an average length of around 5D (D=screw diameter)

An Equivalent mass/design is proposed by NIMESIS than TiNi Aerospace Frangibolts
Nevertheless due to density: TiNi= 6,5 / AlCuNi=7
AlCuNi is slightly heavier
The overall mass impact of this solution shall include the impact of longer screws (+50% of added mass of SMA Washers without consideration of potential volume interference)

4.1.3 NIMESIS products – Active devices

Same mechanical design as previously presented has to be considered with the added implementation of following elements in order to get a LSI compliant version from the MINCO Company.
- Electrical Heater : Flat polyimide
- Thermal sensors: Flat thermocouples foil
- Status sensor: stain gauge / Piezo sensor / impedance check (TBD)

Heaters Reference can be found in redounded double circuit or the options is to stake 2 mono-circuit
Elements selected are:
- NASA S-311-P-079 certified
- ESA ESCC 4009/003 certified

Heaters used for devices like Frangibolt or others must be dimensioned and chosen as a function of the shape memory material.

For a surface density of 5W/cm², the maximum temperature reachable with polyimide heaters is about 150°C. This is convenient for all low temperature (accessible with TiNi Alloys) but not sufficient for high temperature only accessible with CuAlNi.

Nevertheless it is assumed that no disposal case needs an active triggering at such high temperature and then this specific alloy (expect in case on selection one single alloy for all applications)

4.2 Concept 2 : SMA Inserts / Release Screws

This design is assumed to fit M4, M5, M6 classical requirements for end I/F panels

A dedicated design can be derivate for Bobbin inserts and internal panel I/Fs but represent a significant mass impact with regard to initial bobbin insert**.**
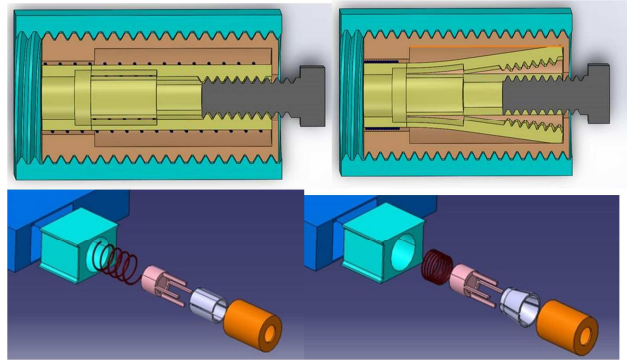

Figure 11: SMA insert design in cut and exploded view

This design is composed of the following parts performing following functions:

- The Sandwich panel – S/C external panel
- The Panel insert – Screwed I/F with different panels
- A SMA Spring or a Ring
    - To maintain the expansible thread in cylindrical shape under bending flexion when SMA is in cold shape (standard extended spring shape)
    - To release the expansible at its conical shape and then release the screw when SMA is in hot shape (increased diameter and compressed shape)
- A part with 4 inserted guides inside thread grooves
    - to avoid any interference between threads & screws during release)
- A 4 petals thread in titanium (baselined) or SMA alloy (as back-up solution)
    - in initial conical shape
    - maintained in cylindrical shape by a SMA Spring under tension
    - The final thread is performed in final cylindrical shape
- An housing cage maintaining all mechanism parts
    - part is screwed-mounted inside the insert panel for replacement capability

The thread part shape and design shall be optimised and demonstrate the deflexion capability at acceptable internal stress level (but this titanium has much less constraint than SMA material)

The above preliminary calculation presents the deflexion force of individual petal thread: (50N / 3mm deflexion)

4.3 Concept 3 : SMA Cutting Cords / Release Panels

This concept can be proposed on 2 study cases:
- Inter Panel Cleats
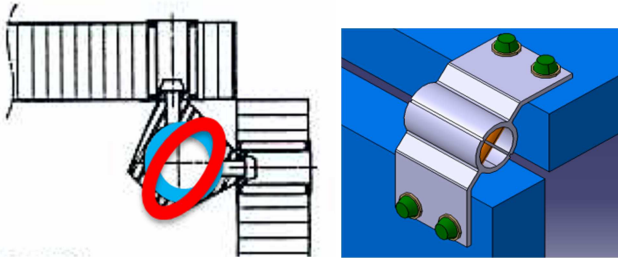- Structural tubular Frames carrying Panels

Figure 12: Concept 3 Applications

The following external design was proposed by ALTRAN:

- An slight external groove is performed on the tube
- Groove width is relevant to cope with ratio of Tube material extension at rupture (20% for Aluminium) and the expansion ration of SMA
- Groove depth is relevant to confirm that overall tube is still resistant enough to sustain the launch loads

The following internal design was proposed by NIMESIS:

- A series of SMA pins provide the needed strength to extend the tube up to rupture tension and groove restriction up to extension at rupture
- A central header (metal or plastic) inserted inside the tube is maintaining the SMA pins
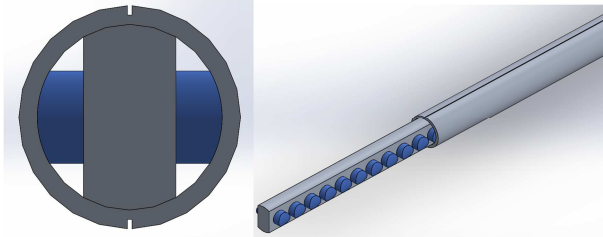
Figure 13: Concept 3 Design Description

The below calculation sheet demonstrates the correct geometry of elements to obtain the required tension to break an Aluminium tube with acceptable SMA stress level in hot shape.

No calculation is presented in cold shape because this solution does not constraint he SMA at cold temperature

The design requires a significant number of SMA pins inside the tube and then a significant mass impact (to be compared with alternative solutions see Chapter Trade-Off)

As said, the design of the groove is very relevant for Aluminium; it could be more comfortable with more fragile material such as Titanium of Carbon parts.

The same design can be extrapolated to cleat bracket with cutting cord tube down to a diameter of 15-20mm.

Loader and tube alloy	Aluminium 7075 T6 SN	NiTi	CuAlNi
Re (Mpa)	505	SMA Material	
Rm (Mpa)	570	Safe T° (°C)	
Density (g/cm3)	2,81	90	150
Module (Gpa)	72	Trig T° (°C)	
Elongation (%)	11	139	224
Tube	Internal diameter (mm)	20	20
	Thickness (mm)	2	2
	Length (mm)	1000	1000
	Fragile heigth (mm)	1	1
	Fragile width (mm)	1	1
	Elongation (mm)	0,11	0,11
	Strength for fracture (N)	1 140 000	1 140 000
	Weigth (g)	182,6	182,6
SMA Pin	Diameter (mm)	10	13
	Useful length (mm)	17,32	15,20
	Maximum elongation (mm)	0,55	0,49
	Stress (Mpa)	200	150
	Strength (N)	15708	19910
	Pins quantity needed	73	58
	Weigth (g)	10,13	18,98
Loader	Loader thickness (mm)	2	2
	Total pins length (mm)	730	754
	Space between 2 pins (mm)	3,65	4,17
Total	Total pins weigth (g)	**739,6**	**1100,9**
	Loader weigth (g)	80,18	69,13
	Total loader length (g)	819,79	1170,02
	Total assembly length (g)	1002,36	1352,59

Figure 14: Concept Design justification

4.4 Concept 4: SMA Sleeve/ Release Struts , Bars & Booms

This concept can be proposed on 2 study cases:

- Payload Module maintained by tubular struts
- External payload antenna bars or booms

The design is composed of a SMA sleeve tightening a tube ends. Usually those struts are composed with carbon RTM bars. It is then considered that tubulars have to be encapsulated and glued inside metallic ends. Both bars are in contact via those metallic end fittings. The overall SMA sleeve encapsulate in fact metallic end fittings in order to get friction factor under control which is essential to get a proper fitting to transmit loads.

Due to constraints present inside the SMA sleeve in the cold shape , the design of the sleeve represent a significant thickness and length to dissipate the stress in an acceptable level for the cold shape 50-75Mpa.

Nevertheless as soon as the transition temperature is achieved, the SMA inflates and releases both bar ends and the attached springs translated the 2 sleeves along the 2 bars in order to allow the 2 bars struts to be properly cut and free in all directions. The translations of the sleeves avoid the bar to translate along the sleeves which would avoid the strut release due to the angle between the 2 bars.
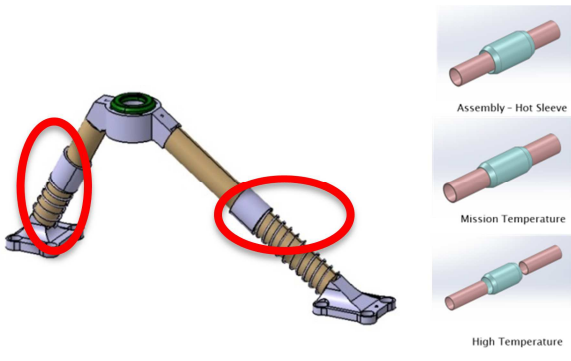
Figure 15: Concept Design justification

The following results can then be considered as baseline for the 2 options P/L (250/500Kg)

		Sleeve under frettage constraint				Glued Sleeve without constraints			
Length	mm	70	70	70	70	50	50	40	40
Diameter Int	mm	22	27	27	30,0	22	27	27	30,0
Thickness	mm	2	2	2,5	3	2	2	2,5	3
Int/ext Dia Ratio	(-)	1,10	1,08	1,10	1,11	1,10	1,08	1,10	1,11
AMF expansion	%	8	8	8	8	8	8	8	8
Increased DIA	mm	23,76	29,16	29,16	32,4	23,76	29,16	29,16	32,4
Density	Rho	6,5	6,5	6,5	6,5	6,5	6,5	6,5	6,5
Weight	Grams	68,61	82,91	105,42	141,51	49,01	59,22	60,24	80,86
Masse P/L	Kg	250	250	500	500	250	250	500	500
Acceleration	G	20	20	20	20	20	20	20	20
Max load	Kg	5 000	5 000	10 000	10 000	5 000	5 000	10 000	10 000
Nb of Bars	(-)	6	6	6	6	6	6	6	6
Bar Strength	Kg	833	833	1 667	1 667	833	833	1 667	1 667
Bar Strength	N	8 167	8 167	16 333	16 333	8 167	8 167	16 333	16 333
Friction	(-)	0,21	0,21	0,21	0,21	0,21	0,21	0,21	0,21
Radial Tension	N	38 889	38 889	77 778	77 778	38 889	38 889	77 778	77 778
Contact Surface	mm²	4 838	5 938	5 938	6 597	3 456	4 241	3 393	3 770
Contact Pressure	MPa	8,04	6,55	13,10	11,79	20,00	20,00	20,00	20,00
Sleeve Section	mm²	140	140	175	210	100	100	100	120
Sleeve Stress	MPa	44	44	71	59	110	135	108	100
Coeff	%	35	35	35	35	35	35	35	35
Sleeve Stress VM	MPa	60	60	95	80	149	182	146	135
Yield Limit	MPa	700	700	700	700	700	700	700	700
Ratio to Yield	%	6,32	6,32	10,11	8,42	15,71	19,29	15,43	14,29
Rupture Limit	MPa	950	950	950	950	950	950	950	950
Ratio to Rupture	%	4,65	4,65	7,45	6,20	11,58	14,21	11,37	10,53
Stress Evolution in T°	MPa/°C	2,3	2,3	2,3	2,3	2,3	2,3	2,3	2,3
Delta T° (SAFE/TRIG)	°C	19,22	19,22	30,75	25,63	47,83	58,70	46,96	43,48

Figure 16: Concept Design justification

As this initial design represented a significant mass impact , an alternative solution has been investigated with SMA sleeves directly glued on carbon bars. But, without dedicated tests in temperature this alternative glued option cannot be fully confirmed today.

Total mass is presented and comparison for trade-off with 4 x M6 screw equivalent is presented in Total/4
Due to density: TiNi = 6,5 / AlCuNi =7 AlCuNi is slighty heavier for equivalent resistance.
Moreover, the use of AlCuNi for D4D application (large range of temperature) implies for thermal expansion reason to use Stainless Steel Screws (CTE = 15) to with match CuAlNi (CTE=17)
This leads to a delta mass impact of +50% with CuAlNi versus TiNi.
So in any case, this concept 4 appears as mass costly to be compared in the final trade-off with competitive solutions.

5   Shape Memory Alloys

19] Shape Memory Alloys (SMAs) refer to a group of materials which have the ability to return to a predetermined shape when heated. The shape memory effect is caused by a temperature dependent crystal structure.

When an SMA is below its phase transformation temperature, it possesses a low yield strength crystallography referred to as Martensite (see Stress-Strain figure). While in this state, the material can be deformed into other shapes with relatively little force. The new shape is retained provided the material is kept below its transformation temperature.

When heated above this temperature, the material reverts to its parent structure known as Austenite causing it to return to its original shape (see Phase Transformation figure). This phenomenon can be harnessed to provide a unique and powerful actuator.
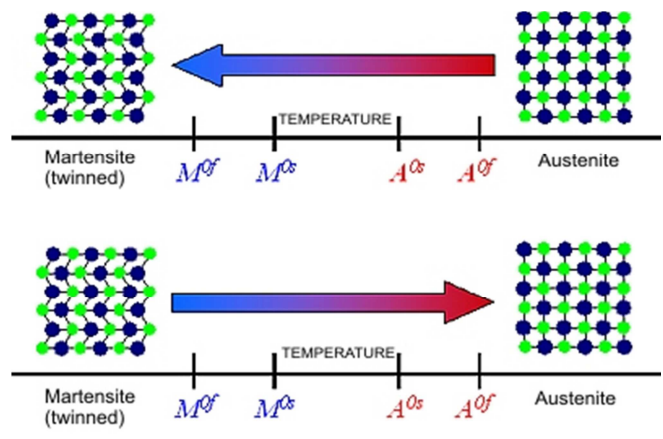

Figure 17: SMA Cristal structural behaviour

Although many shape memory alloys are known, many are at the research stage or have not been commercially exploited. In fact to date there are only two types of commercially available shape memory alloy; NiTi alloys and Cu-based alloys (typically CuAlNi and CuZnAl).

NiTi alloys are the most commonly used shape memory alloys. Typical compositions ranging between 49 and 51 at% have transformation temperatures in the range of -50 to 100°C. These materials have high ductility and have a high level of recoverable strain, ~6-8%. These alloys are readily available in a number of forms from a range of suppliers and are widely known as "Nitinol".

Cu based alloys are relatively expensive and are difficult to produce when compared to NiTi alloys. However, they have much higher recoverable strain limits, typically ~10% for monocrystalline materials.

CuAlNi alloys, although requiring more complex processing conditions than CuZnAl alloys, have a greater appeal commercially. They are capable of

transformation temperatures up to +200°C and are more thermally stable than CuZnAl alloys making them suitable for use at elevated temperatures (>100°C). However, the upper limit for transformation temperature tends to be ~160°C after which the reliability of these alloys does start to decrease. In addition they display a superior shape memory effect than the CuZnAl alternatives.

High temperature shape memory alloys are a strategic material for many applications. If we have a look at the literature we can find many researches on this subject.

Indeed, research studies have been undertaken into alloys with even higher transition temperatures than those demonstrated with the Cu-Al-Ni range. Some of these have focused on Cu alloyed with elements such as Zr. In one such study researchers performed a range of Cu-Zr-Co alloys; they observed a transformation temperature around 280°C in the binary alloy Cu50Zr50. With increasing Co content these values were observed to decrease and in the alloy with the highest Co content (composition Cu45Co5Zr50) these values had been reduced to 166°C and 172°C accordingly.

Another development in high temperature shape memory alloys has been recently reported by the Naval Research Laboratory. They report shape memory transition temperatures varying from near room temperature up to 1100°C in near-equiatomic Nb-Ru materials and up to 1400°C in near-equiatomic Ta-Ru materials. They have also observed significant strain recovery in the region of 4 to 5%.

These researches show the potential and the commercial appeal of these high temperature shape memory alloys. The major reason is that at this high temperature there are no substitutes. This means that CuAlNi could be the unique solution in different applications.

Option 1: Low Temperature : Ti-Ni Alloys

Only one TiNi Alloy reference can be used for our application. Transition temperature is at highest alloy capability **up to 100°C**

It has been demonstrated that NIMESIS has the industrial capability and alternative supply sources to counter-act the US quasi-monopole supply source of those standard and well-known SMA reference
It has been demonstrated that those low temperature SMA are:
- Acceptable in preloaded applications where internal conditions accept low temperature activation (around 100°C)
- Very marginal on non-preload application due to safe margin to be considered with activation temperature

Option 2 High Temperature : Cu-Al-X Alloys :

Several Alloy reference can be used for our applications (X=Ni, Al, Be) . Transition temperature is adjustable in a large temperature range **up to 170-210°C**

It has been demonstrated that NIMESIS has the unique innovative capability to offer SMA with high temperature activation [7]
It has been demonstrated by a dedicated trade-off that this material is the most suitable for the different temperature range requested for the different applications requested on a re-entering S/C (internal / external cases or in-between)
It is noticed that TRL of this material is not yet high and will dedicated characterisation and validation. Nevertheless some dedicated studies are on-going (TAS & R&T CNES)

Option 3 : Very High Temperature : Ti Ni-X Alloys

A lot of several different alloys can be investigated (X=Pd, Pt, Au, Hf, Zr, Ta, Nb) but further investigation and characterization will be needed to get proper data.

Transition temperature would be adjustable in a larger temperature range **up to 250-300°C**

It has been presented that NIMESIS has the unique innovative capability to investigate SMA with very high temperature activation.
It is foreseen that those SMA could have application in external S/C in all cases with better mechanical behaviour and mass saving at system level and the, this innovative alloy could fit every S/C application
It is noticed that TRL of this material is very low and will need dedicated investment for intensive investigation characterisation and validation.
Those materials are nevertheless assumed to have very fruitful spin-off for space and ground industry for safety purposes.
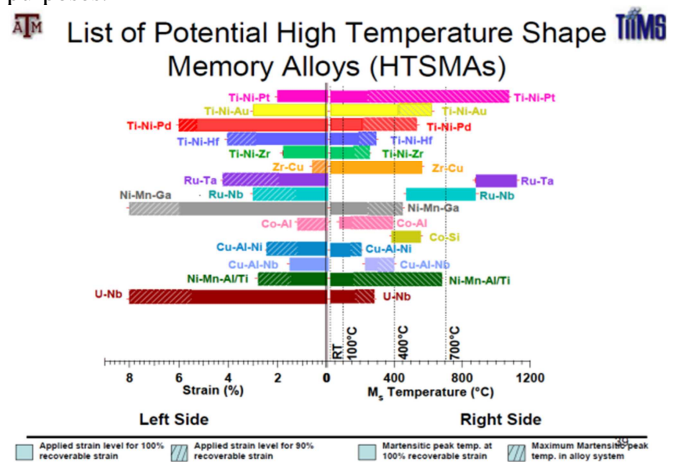

Figure 18: List of High temperature SMA

6   JUSTIFICATION & ANALYSIS

6.1   Mechanical Analysis

6.1.1   Concept 2: SMA Inserts

The thread part shape and design shall be optimised and demonstrate the deflexion capability at acceptable internal stress level (but this titanium has much less constraint than SMA material)

The above preliminary calculation presents the deflexion force of individual petal thread: (50N / 3mm deflexion)
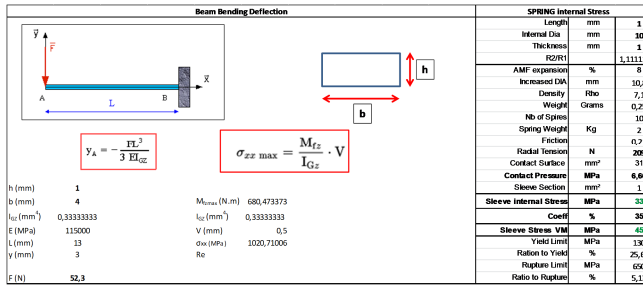

Figure 19. Preliminary calculation (deflexion , loads)

The release spring or ring internal stress was calculated as an equivalent ring 1x1mm diameter with internal pressure load equivalent to 4 petal radial tension of 250N.

This leads to an acceptable stress level compatible to SMA cold shape (around 50MPa internal / Max 64Mpa at surface contact).

The thread part and material shall still demonstrate the correct maintain of stress in the long term under creep effect (not a strong requirement in EOL under microgravity).

Otherwise, the alternative would be to implement a SMA part for the thread as well. It has not been baselined in order to maintain qualification status on titanium material between screw and thread.
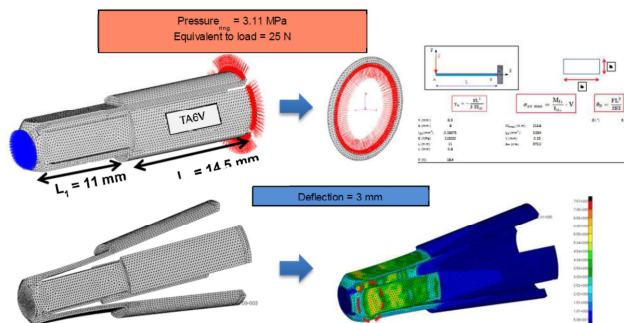
Figure 20: NASTRAN FEM analysis on conical thread

6.2   Thermal Analysis

This section intends to clarify the active heating capability and performance of active SMA Washers (frangibolts) proposed by NIMESIS

This capability will be compared to TiNiAerospace performance as presented on their catalogue [19] reported hereafter for M6 Frangibolt (used as reference) The electrical power is 80W @28V (2,85A) on a 15cm² total surfaces:
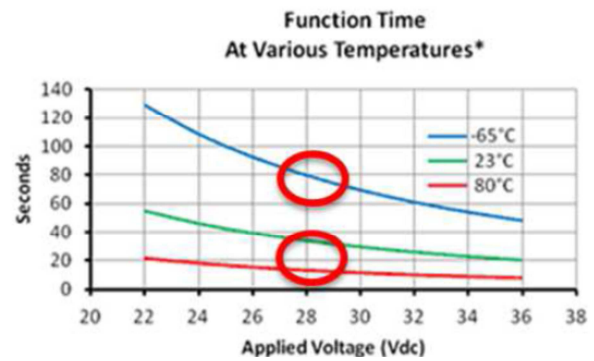
Figure 21. TiNiAerospace Performance for M6 equivalent –(assumed not in vacuum)

The technology proposed by NIMESIS is based on flat FEP heaters (MINCO Corporation)
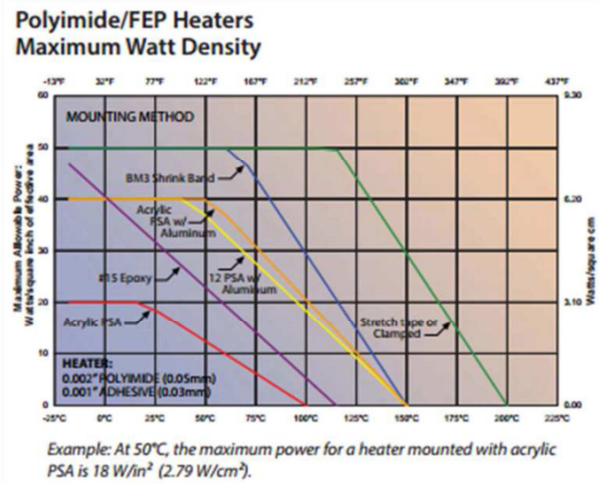

Figure 22: MINCO Heater Electrical Performance

The thermal analyses performed by ALTRAN on ESATAN/ESARAD are with simulation nodes matching with representative H/W and thermal dissipation via

- Thermal coupling (wires , mounting interfaces)
- Thermal radiative dissipation (external faces)

The most representative node as worst case for TRIG temperature is Node 215 (washer internal diameter close to main thermal coupling dissipation).
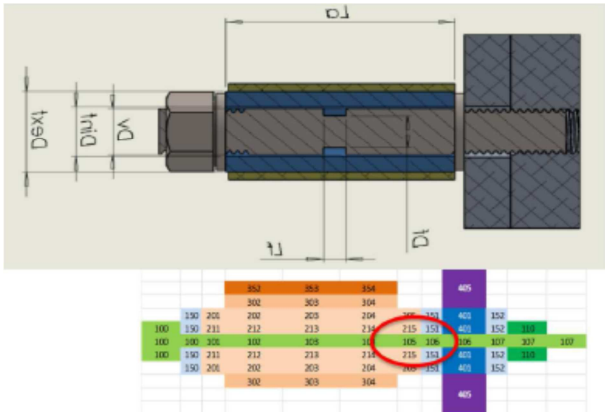
Figure 23. NIMESIS design / ALTRAN simulation nodes

ALTRAN/ESATAN Thermal Analysis results considered following design assumptions

- PWR = 5W/cm² => 20,8 W total (28V/0,75A)
- PWR = 2W/cm² => 52,8 W total (28V/2,25A)

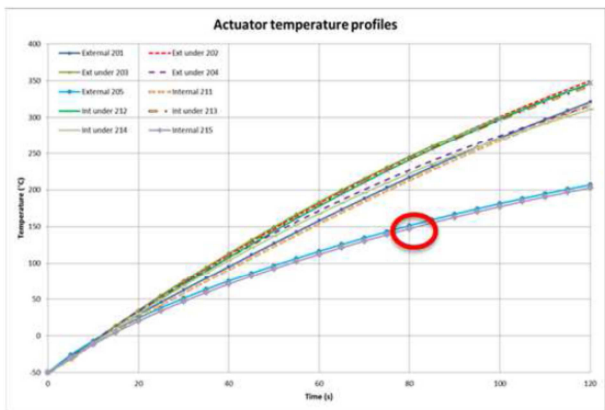And demonstrated following heating time in worst conditions (Cold Case -50°C)

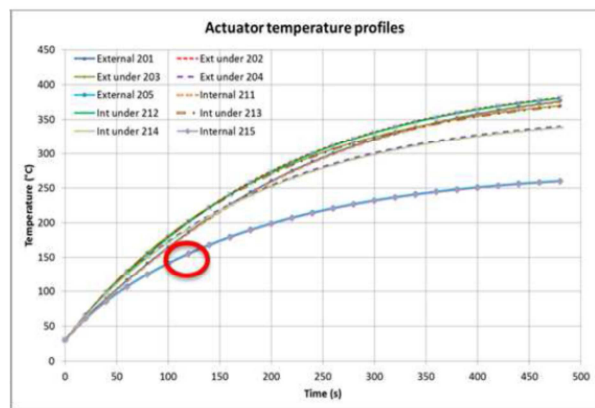*Figure 24. PWR = 5W/cm², time >80s in Cold Case*

Figure 25. PWR = 2W/cm² , time >250s in Cold Case

6.3   Re-entry Analysis

It has been investigated by ALTRAN the capability to couple DEBRISK re-entry Analysis and ESATAN S/C models. It allows with DEBRISK to get mostly trajectory during re-entry in order to determine early aerothermal flux and with ESATAN to obtain thermal radiative and conductive coupling inside a S/C model after injection of input aerothermal data in an equivalent aerothermal flux injected as an additive solar heat flux .

The technique has the tremendous advantage to be able to manage real industry standard S/C model as used for S/C design justification (CDR Datapackage) and qualification test (Thermo-balanced and correlated by tests) and then to provide accurate external and internal data

The following reentry analysis has been performed on a Sentinel-3 on CNES DEBRISK S/W with several jobs in cascade in order to obtain final orbits (real and corrected altitude versus time).
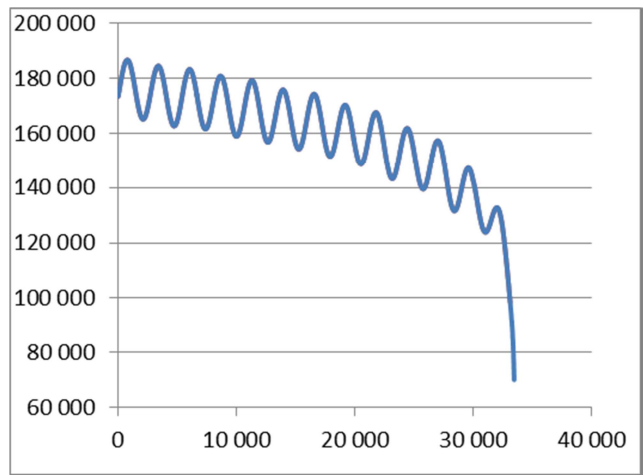

Figure 26. DEBRISK jobs early re-entry trajectory

Thereafter the aerothermal is recalculated considering altitude and velocity considering the usual formulas for the free molecular regime
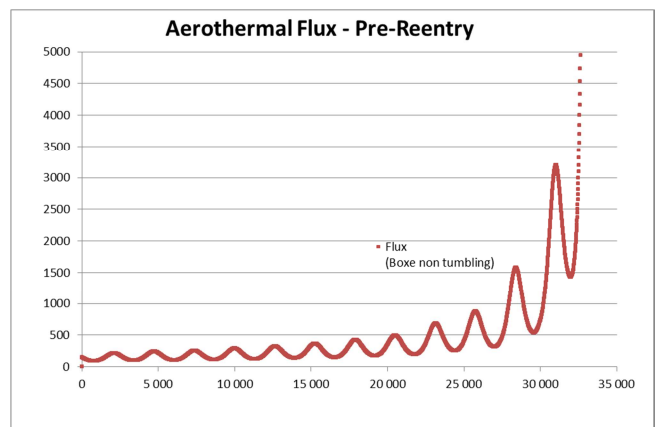

Figure 27. ALTRAN recomputed early re-entry flux

This technique is a unique opportunity to assess S/C thermal characterisation in early re-entry without the need of HTG – SCARAB S/C and medialisation which is unfortunately not accessible to industry.

This simulation on a ESA Sentinel-3 like model gave the following results considering a stable attitude due to solar arrays panel acing as a tail drag until demise around 100 km . (This rough assumption on S/C behaviour has been confirmed by HTG).
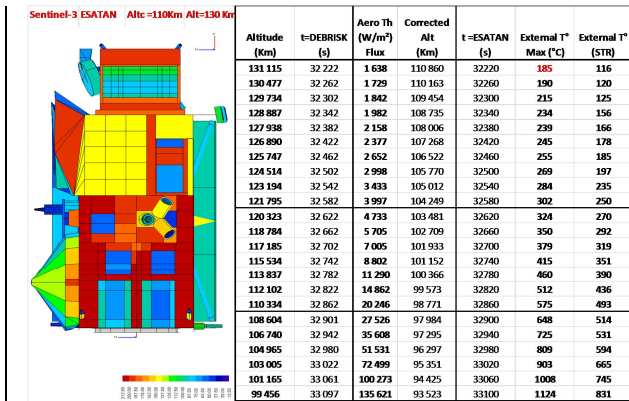

Altitude (Km)	t=DEBRISK (s)	Aero Th (W/m²) Flux	Corrected Alt (Km)	t =ESATAN (s)	External T° Max (°C)	External T° (STR)
131 115	32 222	1 638	110 860	32220	185	116
130 477	32 262	1 729	110 163	32260	190	120
129 734	32 302	1 842	109 454	32300	215	125
128 887	32 342	1 982	108 735	32340	234	156
127 938	32 382	2 158	108 006	32380	239	166
126 890	32 422	2 377	107 268	32420	245	178
125 747	32 462	2 652	106 522	32460	255	185
124 514	32 502	2 998	105 770	32500	269	197
123 194	32 542	3 433	105 012	32540	284	235
121 795	32 582	3 997	104 249	32580	302	250
120 323	32 622	4 733	103 481	32620	324	270
118 784	32 662	5 705	102 709	32660	350	292
117 185	32 702	7 005	101 933	32700	379	319
115 534	32 742	8 802	101 152	32740	415	351
113 837	32 782	11 290	100 366	32780	460	390
112 102	32 822	14 862	99 573	32820	512	436
110 334	32 862	20 246	98 771	32860	575	493
108 604	32 901	27 526	97 984	32900	648	514
106 740	32 942	35 608	97 295	32940	725	531
104 965	32 980	51 531	96 297	32980	809	594
103 005	33 022	72 499	95 351	33020	903	665
101 165	33 061	100 273	94 425	33060	1008	745
99 456	33 097	135 621	93 523	33100	1124	831

Figure 28. ESATAN Post-Processing Data

Conclusions:

As a preliminary result on those studies, the delta temperature between SAFE & TRIG temperature provided by SMA Min 30-50°C seems always compatible to the heating profile (internal / external) experienced during those simulations. This heating profile related to the timing and therefore expected triggering altitude.

External Case: 30-50 °C => 5 – 15 min => 10-30 Km Delta Altitude => 130-100km

Internal Case : 30-50 °C => 10 - 20 min => 20-40 Km Delta Altitude => 130-90 or 120-80km

Lessons learnt:

S/C thermal characterization in early reentry needs to be better characterized for the purpose of early release of elements (whatever the technology is used).

Those uncertainties may lead to reconsider some assumptions made in the present study on thermal Internal / External worst case environment.

ALTRAN proposal to find an alternative way of simulation seems to be working with preliminary correlation performed. But added correlation with current S/W SCARAB would be fruitful for both

- SCARAB increase of accuracy with S/C thermal model behaviors as tested
- ALTRAN increase of relevant S/C data provided at lower altitude and flight regime.

Another main lesson learnt is that behavior BEFORE

reentry is definitively not well understood and characterized today. Even if some Safe Mode cases are substantiated during S/C development. The need to further investigate the complete free-flight mode after disposal (25years reentry rule) remains mandatory. Several aspects are contributing to a lot of uncertainty:

- S/C attitudes
- S/C thermal geometry
- S/C architectural H/W (Alu Panel / Carbon Panels)
- MLI status

(Ageing and degradation assumption in this phase).
Those aspects in a better / worst case scenario may raise a lot of deviation in the results

Good news is that whatever the results of those studies will gave in the future, SMA always provide the capability to be adjusted to re-use the same demonstrated mechanisms. It has been demonstrated that AlCuNi is probably the most versatile alloy selection allowing a large range of solutions with adjustable temperature activation with no modification of material parameters allowing to cope the mechanism H/W design for several temperature selection.

6.4   Demise Analysis

The proposed materials implemented in the proposed devices have the following Qdemise preliminary assessment (Heat for demise):

TiNi >> 1000 KJ/Kg (problematic)
CuAlBe > 1000KJ/Kg (likely problematic)
CuAlNi <= 1000KJ/Kg (not problematic)

If the proposed material SMA-HT (CuAlNi as baselined by NIMESIS) do not represent any demise issue, the main uncertainty remains on TiNi (Low Temperature) which can be used for internal application cases

A dedicated reentry analysis is needed to assess the demiseability of those TiNi devices when applied to in large parts and quantity (Frangibolts and Sleeves).

Conclusions of Reentry Analysis performed on CNES DEBRISK S/W Conclusions are:

- No Frangibolt is surviving (even tested with Full Titanium on M12)
- No TiNi Sleeve are Demising (When tested with full Titanium)
- Tini Sleeves are marginal at large diameter

(OK for Dia 20-25 in full Nickel- Marginal at Dia 37mm : 67J)

Figure 29: DEBRISK Analysis Results

7   CONCEPTS OPTIMISATION

A further and final engineering phase has been initiated by NIMESIS on Concept 1_SMA Wahsers which complete datasheet is now available as Triggy- NT and HT concepts:
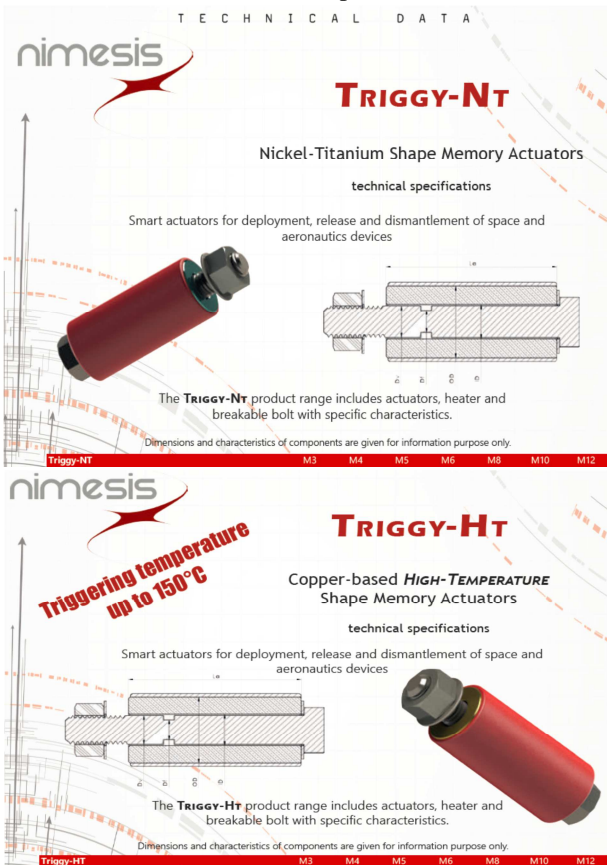

Figure 30. NIMESIS Triggy Devices Datasheet

A further and final engineering phase has been initiated by ALTRAN 2 on Concept 2-SMA inserts iterating on
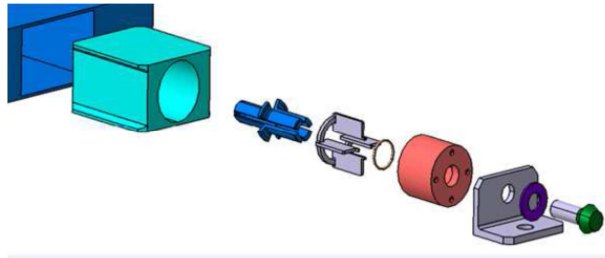
several variants if conical device release insert.

Figure 31.Final optimised conical variant

This added study leads to optimise the SMA insert concept to a more shorter and cylindrical insert able to fit inside most honeycomb panel thickness and then fit all S/C panel applications such as bobbin insert in a lighter, easier variant.
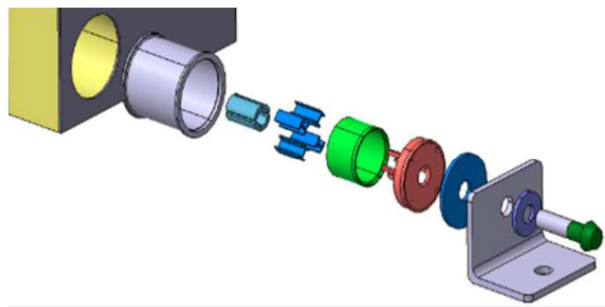
Figure 32: Final shorter and cylindrical variant

8   TRADE-OFF & SELECTION

Hereafter is presented the overall synthesis of the different concepts and variants addressed in the scope of this study.

The concepts are trade-offed on the specific study case of a M6 screw. The other cases are mass reported as an equivalent single I/F with consideration of 10 screws per cut-cord bar or 4 screws per SMA Sleeved strut.

Figure 33: Trade-Off on Overall Study concepts

	TRL NASA Mankins Scale	Specific Rankings		
Irrealistic/Immature Concept	0		INACCEPTABLE	
Technology Concept	1-2	>50	Hardly Acceptable	
Prototype Demonstration	3-4	>40	Acceptable pending Impa	
Demonstrator Validation	5-6	30/40	Almost Transparent	
Flight Qualification	7-8	<30	Transparent / Attractive	
Flight Proven	9	<20	FULL ADVANTAGES	

With the usual colour code, the ranking is assessed and the decision for the Technological Building Block is as followed:

Concept 1 _ SMA Washer / Frangible Screws

This proven concept 1 is maintained for the Technological Building Block

It could be considered as a back-up solution to ensure the baselined concept 2 which has still some demonstrations needed and risks in development.

It can be proposed in 2 versions (active & passive)

It better shall be developed in 2 SMA Versions to be more mass-attractive

Concept 2 _ SMA Inserts / Release Screws

This promising concept 2 is proposed for the baselined Technological Building Block

It can be proposed in 2 versions (active & passive)

It could be in one single SMA version (CuAlNi) able to be tuned at material process without insert change of design to set the needed triggering temperature.

Concept 3 _ SMA Cutting Cord / Release panels

This concept has then been discarded from the Technological Building Block

Concept 4 _ SMA Sleeves / Release Struts & Booms

This concept has then been discarded from the Technological Building Block as attractive to fewer applications.

9   STUDY OUTCOMES

All TRL assessed here are considered at end of the currents study "ESA Cleansat Technological Building Block assessment.

All following concepts have been presented and substantiated and achieve following TRL

Concept 1 : SMA Washers / Frangible Screws
- TRL 9 in space industry with TiNi Aerospace products Low temperature – active solutions
- TRL 5-6 at NIMESIS currently based on latest development (on-going)

Concept 2 : SMA Inserts / Released Screws
- TRL 3 on ALTRAN device (long conical insert)

TRL2 on ALTRAN device (short cylindrical insert)

Concept 3 : SMA Cutting Cords
- TRL2 on ALTRAN/NIMESIS device

Concept 4 : SMA Sleeve / Release Struts, Booms
- TRL 2 on ALTRAN/NIMESIS device (Struts)
All those above concepts are mostly driven by the SMA material characterisation and qualification and need a dedicated TRL assessment .

Option 1 : Low Temperature : Ti-Ni Alloys
- TRL 9 in space industry with TiNi Aerospace
- TRL 5-6 at NIMESIS currently based on latest development with TAS & CNES R&T

Option 2 : High Temperature : Al-Cu-X Alloys :
- TRL 5-6 at NIMESIS currently based on latest development with TAS & CNES R&T

Option 3 : Very High Temperature : Ti Ni-X Alloys
- TRL 1-2 in SMA industry throughout the world (as understood at NIMESIS)
- TRL 2-3 at NIMESIS currently (see SMA-UHT presented state of the art)

10   ROADMAP

The present section will present the roadmap to develop the consortium-selected concepts and characterize SMA alloys requested by the specificities of D4D applications and operational cases investigated along this study.

- **Concept 2 : SMA Inserts /** Release Screws
  as the baselined option
- **Concept 1 : SMA Washers /** Frangible Screws
  as the back-up option

It is pointed out that presented roadmap is with assumption of development / demonstration phase with the same consortium (NIMESIS / ALTRAN) under ESA follow-on contract. As a reminder the scenario assumption to have a LSI prime contractor in the loop in the development and validation and common engineering on dedicated applicative case would probably more efficient to get a product a higher TRL.

All proposed concepts will have to go to formal EQSR process (Equipment Qualification Status Review) but all concepts can be preliminary assessed at category D (full re-design / full requalification in the related ECSS reference frame)

Moreover, in preliminary of those devices development, Material further demonstration and characterisation will be required

- **Option 1 : Low Temperature : Ti-Ni Alloys**

TRL at NIMESIS is high enough and alloy behaviour knowledge is good enough to foresee no specific material characterization.
Nevertheless some added validation will be requested to demonstrate the compliance for space environment and long term actuation.
(SMA actuation devices never had the long lifetime requirement as always used at beginning of Life)
Those dedicated accelerated lifetime Test sequence are usually long (1-2 years TBC) but not necessarily costly (<100KE)

- **Option 2 : High Temperature : Al-Cu-X Alloys**

TRL at NIMESIS is relatively low but probably the highest in world material industry
This TRL is under process with TAS application and under CNES R&D
The dedicated applications for passive devices (scope of this study) will require specific characterizations on materials. (1-2 years, some 100KE)
The same dedicated lifetime tests as options will be necessary

- **Option 3 : Very High Temperature : Ti Ni-X Alloys**

TRL at NIMESIS is very low as probably everywhere in the world material industry.
Those materials will require dedicated investments for intensive investigations for characterization and validation. (Several years, several 100KE)
After this phase, the same amount of dedicated lifetime tests as options will be necessary

In addition to all those demonstrations, each application will require a case by case study to clarify the local S/C re-entry thermal characterization, in addition to the clarification of the internal level of constraints inside SMA material due to the applicative case. Only after dedicated those accurate analysis, the safety and triggering temperature for SMA will be determined and then the application will be correctly substantiated in front of Space Debris Requirements

10.1 Risks Assessment

➢ **Concept 2 : SMA Inserts / Release Screws**
(as baselined)
This concept is at development risk, mostly because current status is around TRL3 and need further confirmation by test and still design and process consolidation.
➢ **Concept 1 : SMA Washers / Frangible Screws**
(as a back-up)

This concept is at very low development risk, mostly because current status is above TRL3and basic concept has already heritage and design and process are simple.

➢ **Variant 1.TiNi Material**
The material is under procurement basis by NIMESIS, with low visibility on the process. Moreover those are Chinese or American materials dealing with some potential ITAR or EAR risks

➢ **Variant 2.AlCuNi Material**
The material will be under production/procurement basis by NIMESIS, with high visibility on the process due to the need of NIMESIS involvement in process procedure. (2 foundry suppliers selected)
(High sensibility to the chemical composition of the alloy needs in situ characterisation in the foundry during the casting).
NIMESIS is under full control of the process due to patent 15 6084 on CuAlNi

➢ **Variant 3.TiNi-X Material**
This material will be complicated to procure or elaborate needing specific machine /investment to be purchased by NIMESIS. Few or no knowledge of very long term effects or susceptibility
This approach needs to be consolidated in our Roadmap approach or funded with other application purposes (H2020 etc..) and retrofitted to our device if available in the future

10.2 Assembly Integration and Tests

The following test models and sample will be needed
· Material samples
           (production / procurement / Process batches)
· Device breadboards (concepts & variants)
· Devices Prototypes (selected concepts)
· Devices PFM Units (selected study cases)
· Panel Mock-up (selected study cases)

11   CONCLUSION

The study focused on 2 main presentations

Technological Devices: Panel of dismantlement devices aimed to cover most S/C needs for DCA improvement during re-entry

SMA Materials: Panel of materials aimed to cover the complete activation temperature range with safe margin against accidental release

The proposed study has demonstrated the technological capability of proposed devices to achieve the intended dismantlement function in compliance with LSI requirements.

All concepts have been substantiated in dedicated

realistic study case. (Release panels, release appendages, release S/C modules)

Mechanical loads and environments have been correlated with SMA internal stress capabilities

Thermal requirements have been checked in term of SAFE and TRIG temperature with regard to regard to the specific study cases.

Heating time and release altitude have been demonstrated compliant to the expectations.

The dismantlement techniques have already demonstrated their relevant capability to reduce S/C DCA (Debris Casualty Area).

The expected order of magnitude of DCA reduction that can be achieved is up to an order of 2 (with addition of other D4D techniques).

This SMA dismantlement option appear as the most suitable solution to trigger at a requested temperature range with regard to alternative technologies (Pyro, Glued I/Fs, ..)

This option with SMA behaves as real release mechanism. A complete set of devices has been presented for S/C applications. The mechanisms can be very standard The solution can be adjusted in temperature with the same alloy reference without changing the device H/W design for a same application (still compliant with the stress level required by the application).

The concepts proposed for further CLEANSAT Technological Building Block development are:
➢ **Concept 2 : SMA Inserts /** Release Screws
    As the baselined option
➢ **Concept 1 : SMA Washers /** Frangible Screws
    As a safe and alternative back-up option

The added concepts 3 (SMA Cutting Cord) & Concept 4 (SMA sleeves) presents today less interest and need added test sequence at breadboard level to confirm their capability and assumptions made in this study.

NOTA: Lessons learnt on that study clearly highlighted the need to further characterise the thermal S/C environment in pre-re-entry Phase (25 years disposal) and early re-entry (150-120Km).

ALTRAN has initiated the capability to analyse standard ESATAN S/C thermal model in this pre-reentry environment. A dedicated paper will be published this year to present the outcomes of the work initiated with this study.

13   ABREVIATIONS AND ACRONYMS

ADS	AIRBUS Defense Space
CNES	Centre National D' Etude Spatiales (French Space Agency)
DCA	Debris Casualty Area
DEBRISK	CNES Low Fidelity Reentry S/W
DRAMA	Debris Risk Assessment and Mitigation Analysis
EQSR	Equipment Qualification Status Review
ESA	European Space Agency
FIT	Failure in Time (1E-9)
HTG	Hyperscall Technology Goettingen (SCARAB S/W developper)
NIMESIS	French Shape Memory Alloy designer
OHB	Orbitale Hochtechnologie Bremen - Orbital High-Technology Breme
LSI	Large Simple Integrator
P/F	Platform
P/L	Payload
R&D	Research & Development
S/C	Spacecraft
SCARAB	ESA High Fidelity Reentry S/W
SMA	Shape Memory Alloy

TADAP	TAS-I Reentry S/W
TAS	THALES ALENIA Space
TBC	To Be Confirmed
TBD	To Be Defined
TRL	Technology Readiness Level

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