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BFS « Back From Space », an atmospheric reentry kit for Newspace application

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Abstract
The atmospheric reentry technologies have not evolved significantly since the early days of space exploration. Mostly they were designed for manned spaceflight applications allowing humans to return safely to Earth in a capsule or shuttle-like vehicle. Those applications have all the drawbacks that return vehicles whose shapes were constrained by launch phase restrictions (cross-section of the capsule or of the heat shield under fairing, aerodynamic shape of the shuttle). The next generation of reentry systems intends to disrupt this constraint with the deployment of a larger heatshield via an inflatable or deployable heatshield composed of flexible or textile thermal protection systems. If those concepts are not completely new and have already been intended in the past more than 2 decades ago, their implementation on operational applications seems to be finally underway. (H2020 EFESTO, NASA ADREPT, …).
The trends for NEWSPACE and for GREENSPACE for a more industrial and sustainable use of space have reactivated the interest in reusable systems and recovery of elements from space in a more innovative manner (in-orbit manufacturing and production, short-time recovery of experiments out of ISS resupply cargo 6-month routine.).
Due to its past experience in reentry topics coming from past activities in Design for Demise in a research entity of the ALTRAN Company, the e.NOVA start-up was created by his founder to promote this legacy and top-listed this project BFS “Back from Space” as a main initial objective and initiated a consortium with industrial textile and composite developers, shape memory alloy provider, thermo-mechanical and computational fluid dynamics analysts.
This paper intends to present the state of the art on this thematic and the initial progress status of this internal project and the legacy reused in this initiative.

1. Introduction

Since the beginning of space exploration, experimentation in space has yielded much knowledge and led to many discoveries benefiting humanity on the ground. To analyse the results of the experiments led in space, instruments and laboratories are needed. Two solutions exist in order to solve this problem: bring the instruments into orbit or bring the samples to a laboratory on Earth. The former is currently the most used solution with such examples as the Columbus module on the ISS or the Mars Science Laboratory on the Curiosity rover. This solution requires the scientific instruments to be adapted to work in the conditions of space and survive the transport to the location (radiation, temperature, G-force during launch, …). In contrast, bringing the samples back to Earth for analysis allows for the use of more delicate instruments that could not survive the launch and use in space. The downside of this solution is that the samples need to have a way to return to Earth and survive the atmospheric reentry. As the Newspace market continues to develop, it pushes the actors to find solutions to make space more accessible to everyone, meaning cheaper with easy solutions. It is to answer this problem that e.NOVA Aerospace has started developing its BFS, or Back From Space, project with several partners.
With the explosion of the use of NanoSats, satellites have become smaller, lighter, and cheaper. This means that the instruments onboard must follow the same trend. Making an instrument space-ready while miniaturising it and making it cheaper is hardly feasible, leaving only the option to bring samples back to Earth for actors of the Newspace. The BFS is an atmospheric reentry kit developed for CubeSats and Nanosats to allow them to reenter the atmosphere safely in order to deliver their payload to the ground. Nowadays, some projects are proposing and developing similar approaches to what the BFS project is searching. The ADEPT program is developing a mechanically deployable re-entry vehicle system for nanosats and spacecrafts [1]. EFESTO [2] or HIAD [3] from NASA opt for an inflatable mechanism instead, which a priori looks closer to the needs of the BFS project.

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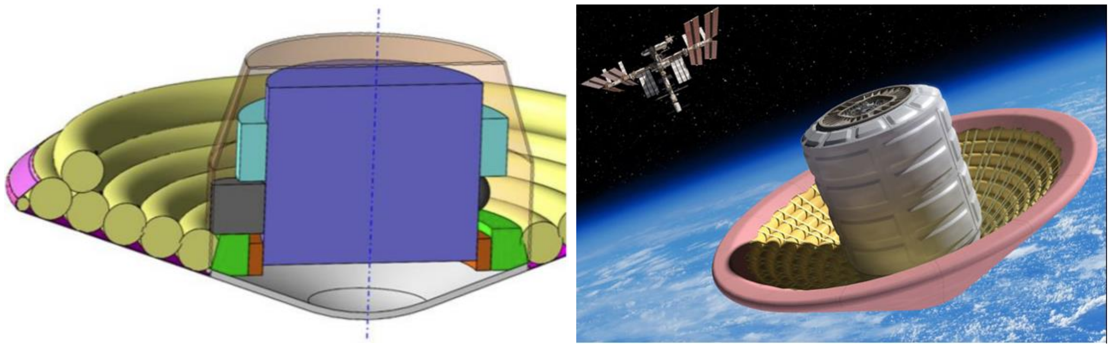

Figure 1: EFESTO's concept design & NASA's HIAD

With its partners NIMESIS [4] working on memory-shaped alloys and IFTH [5] working on flexible thermal protections, e.NOVA leads the development of the project and coordinates with all actors to find the best solutions and clients for the reentry kit. The origins of this project lie in an ESA ITT (Invitations To Tender) led by NITREXO with the aforementioned partners to develop and qualify a Flexible Thermal Protection System for a Martian decelerator. It later evolved to be presented in 2021 at CNES's R&T and Call for Proposals for NanoSat IOD-IOV and led to the BFS project in its current form.

2. Potential Uses

To define the types of missions the BFS should be able to achieve, we need to first define what sorts of payloads could be brought back. The types of payloads can be categorised either as scientific or commercial.
For the scientific payloads, the goal of bringing them back is to offer the possibility to study the payloads on the ground, in laboratories on Earth. In some cases, a return to Earth might not be necessary as telemetry can offer enough useful data. In addition, some experimentations (such as on human physiology) are unsuited for the CubeSat format due to the volume constraints. While limiting ourselves to addressing payloads up to 27U for the BFS, we can still work with experiments requiring different conditions. The BFS can be mounted as rideshare on launchers, allowing it to bring the experiment where it should be (e.g. the Van Allen radiation belts in GTO transfer orbits), keep it there for the specified duration, and bring it back safely for analysis on the ground without human intervention. For more complex experiments that require a human, the BFS offers the possibility to transport payloads from the ISS to the ground on demand, as opposed to the current cargo spacecraft that fly only every six months.
The commercial payloads, as opposed to the scientific ones, represent the products of in-orbit manufacturing. While this market is still in development, it will likely play a major role in the industry of the future for specific, high quality, and high added-value products. Some of these products can be 3D printed organs for medical purposes or high-quality optical fibres.

3. Business Model

To be viable and offer a long-term service, the economic aspect and business model of the BFS need to be studied. As discussed earlier, the field of applications is large but the question of going into orbit has to be considered before we can look at coming back. For this aspect of the payloads life, e.NOVA discussed a collaboration with Nanoracks to offer "early returns" services to their clients. This offer would interest at least 1/3 of Nanoracks' clients, as it gives them the ability to refurbish their experiments quicker, pay for less time on the ISS, and in consequence fly more often. Such types of missions would launch from the ISS's Bishop module at an estimated initial frequency of 4 flights per year. In order to be interesting for a client to use our early return solution, we have to ensure that it is cheaper for them than waiting on the ISS and paying for a spot in a regular cargo spacecraft. As such, we are focusing on making the BFS compact to save on volume and choosing the right technologies to diminish the cost. The choices and the detailed explanation for them will be explored in the following chapter.

4. Mission

The first challenge faced within the project was the study of the re-entry trajectory and the assessment of the reachable landing accuracy. The influence of the different parameters on the final velocity will also be studied, as it will be a key driver of the touchdown system design. The scenario is based on an unguided descent from the surroundings of the International Space Station (ISS) to ground. A Keplerian trajectory serves as a first approach. Nevertheless, it is

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essential to take into account the (huge) effect of the atmosphere. To this end, the software DEBRISK from CNES (Centre National d'Etudes Spatiales) [6] has been used to simulate the atmospheric reentry. Google Earth Pro [7] and MATLAB [8] have been used to plot the results. An auxiliary code made with Python [9] was used to help with the management of the data files (.dat).

The reference is now a spacecraft with 4.5 kg of mass. Several parameters will take part of the final landing accuracy budget. Namely, it can be advance that the ballistic coefficient of the device will be a key driver. In addition, the heating rate must be handled in such a way that the maximum temperatures of the different materials composing the descent device are not reached. Another important factor is the initial velocity; the objective is to avoid the need of a high energy deorbit burn. To this end, the altitude of perigee targeted to reach re-entry thanks to the atmosphere will be of 75 km.

The trajectory to reach a good nominal landing path was determined by iterating with the argument of the perigee and launch window in DEBRISK. As a result, the following orbit parameters were established for a hollow sphere of 4.5 kg and 50 cm of diameter. The material is considered ideal and without ablation.

Table 1: Orbit parameters introduced in DEBRISK

Parameter	Value
a	6615.636 km
e	0.024563
h_a	400 km
h_p	75 km
ω	236.3°
i	51.2°
Ω	356.23°

The descent trajectory with these parameters is shown in Figure 2. It can be seen that it falls perfectly within the desired range of Woomera. This scenario will thus serve as nominal case of reference for the variations that are to be introduced in the different parameters that affect the landing accuracy.

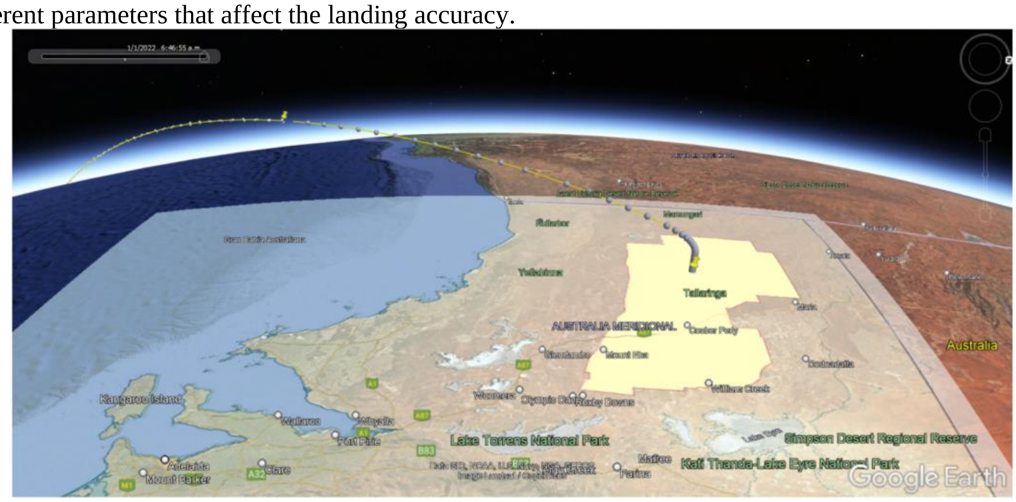

Figure 2: Reentry trajectory

Using MATLAB for further analyses of the results, it is possible to plot the distance to the landing point of the nominal case with respect to the altitude of the perigee set. We find the following expressions linking the variation in downrange (δDR), the altitude of the perigee (δh_p), the argument of the perigee ($\delta\omega$), and the ballistic coefficient (δC_b):

$$\boldsymbol{\delta DR = 18.163 \times \delta C_b} \quad \textbf{(1)}$$

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$$\boldsymbol{\delta DR = 101.9 \times \delta hp} \tag{2}$$

$$\boldsymbol{\delta DR = 140 \times \delta \omega} \tag{3}$$

As we are assuming small variations, the perturbances follow the principle of superposition. Putting equations 1, 2, and 3 together yields the total error in downrange due to the combined perturbations.

$$\boldsymbol{\delta DR = 18.163 \times \delta C_b + 101.9 \times \delta hp + 140 \times \delta \omega} \tag{4}$$

Given all this, Table 2 gathers the measured variations of downrange (ΔDR) for the two analysed worst-case scenarios and the variations estimated by equation 4 for $\Delta DR'$.

Table 2: Worst case landing errors simulated and estimated by equation 4

Scenario	**ΔDR**	**ΔDR'**
First (North)	235.2 km	284.9 km
Second (South)	250.1 km	298.8 km

Knowing that the maximum allowable error is 235 km and having equation 2 that relates the error in downrange with the error in altitude of the perigee, we find that the biggest variation of the altitude of the perigee is of 2.3 km, putting it at most at 77.3 km. In consequence, the smallest Δv necessary is 94.08 m/s, 0.69 m/s less than the nominal boost of 94.77 m/s.

The clear conclusion is that the landing accuracy is extremely sensitive to the value of the impulse Δv. To be safe, a propulsion system capable to provide a boost accuracy of ±0.1 m/s would be required.

5. Propulsion Module

The necessary impulse Δv to go from the ISS to ground was found to be 95 m/s. The minimum power consumption was searched. In addition, the propulsion module was limited to 1 U. Cold gas propulsion was discarded for not offering a sufficient thrust, so warm gas systems were the preferred option searched. After studying more than 60 candidates, the main options were gathered in Table 3, all of them consuming less than 25 W.

Table 3: Main characteristics of the eight propulsion module candidates

Product Name	**Manufacturer**	**Δv_{MAX} @ 4 kg**	**Power (operation)**
Starling [10]	Benchmark Space	140 m/s (estimated)	13 W
CHIPS 1U R134a [11]	CUA Aerospace	123 m/s	25 W
PUC [12]	VACCO	167 m/s	15 W
EPSS C1 [13]	NanoAvionics	280 m/s	?
BGT-X5 [14]	BUSEK	146 m/s	20 W
ENPULSION NANO [15]	ENPULSION	250 m/s (estimated)	10 W (estimated)
PM200 [16]	HYPERION	230 m/s	12 W
nanoFEEP [17]	Morpheus Space	520 m/s (estimated)	12 W

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Summarizing the main features of the studied propulsion system, the following lines can be stated:

- PM200 (Hyperion Technologies) seems to be the best option, offering a maximum Δv higher than 230 m/s according to the manufacturer. It uses a non-toxic bipropellant propulsion with nitrous oxide and propene in a self-pressurizing configuration. This is done with a power consumption lower than 12 W during firing and 0.1 W during sleep mode. In addition, it has a good status of development (TRL-8).
- PUC (VACCO) seems to be a good alternative. With a power consumption of 15W, it can deliver a Δv of 167 m/s. This information is clearly offered in the datasheet of the product.
- ENPULSION NANO and a pack of 4 nanoFEEP (Morpheus Space) also look capable of offering a very good performance with a power consumption not higher than 12W. However, the information provided in their datasheets is not straightforward and their suitability must be confirmed. Another important drawback might be with regards to the burning time. Seeming to be an electric thruster with quite low thrust, it may take too long to acquire the desired increment of velocity.
- Starling (Benchmark) seems to offer acceptable results at low power, but their specifications are not very clear and are to be confirmed after requesting more information.
- With some more watts of consumption CHIPS (CUA) and BGT-X5 (BUSEK) offer good results as well.
- EPSS C1 (NanoAvionics) has very good characteristics but it is not clear how it would be operated (solid propellant).

In conclusion, the PM200 thruster from Hyperion Technologies was deemed to be the best option. It uses a non-toxic bipropellant and presents a good state of development (TRL-8). Nanoavionics' EPSS C1.5 is a good alternative although it is in principle larger than desired (1.5U).

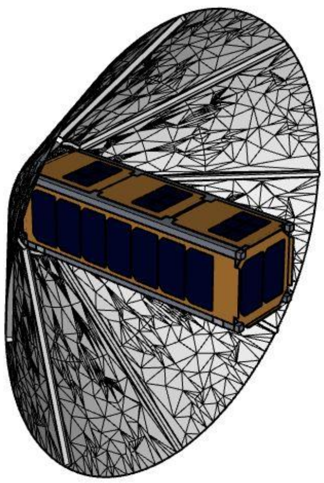

Figure 3: BFS with platform and payload (CubeSat DEMO)

6. System & Components

The following task addressed was to treat the preliminary design of a payload module for a In-Orbit Demonstration / In-Orbit Validation (IOD/IOV) mission. The objective is that this module must collect data during a first re-entry of the BFS device that can serve to validate the concept and to improve further design iterations with real data from the descent. In particular, pressure and temperature measurements are desired to be collected, together with monitoring the position and velocity of the spacecraft during the descent trajectory. 3-axis linear accelerations and the three angular accelerations would be interesting information as well. All the data is to be sent to ground via IRIDIUM link. These requirements, divided into mission requirements (MR), physical requirements (PR), and auxiliary requirements (AR), are presented in Table 4 below along with proposed design solutions.

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Table 4: Payload Module Requirements and associated Design Solutions

	Requirement	Design Solution
MR1	The payload shall measure the temperature and heat flux on the external faces	Thermal flux meters and/or temperature sensors
MR2	The payload shall measure the pressure on the external faces	Pressure sensors
MR3	The payload shall measure the accelerations on six degrees of freedom (linear and angular)	6 degrees of freedom accelerometer
MR4	The payload shall measure GPS position and velocity	GPS antenna (MR4.1) and GPS module receiver (MR4.2)
MR5	The payload shall transmit the data to ground	Iridium antenna (5.1) and Iridium modem (MR5.2)
PR1	The payload module shall fit in a 1U format	N/A
PR2	The payload module interface is TBD	N/A
AR1	The payload module shall manage the data acquisition and transmission	On-Board Computer (OBC) and on-board software
AR2	The payload module shall receive the necessary power supply	Electrical Power Supply System with batteries and regulation system

Having defined the preliminary set of requirements for the payload module and design solutions for them, hardware choices were made to address them. The choices are presented in Table 5.

Table 5: Payload Module Hardware Choices

Req.	Hardware	Manufacturer	Ref.
MR1	Temperature and thermal flux meters	Instrumental Thermal Instrument (ITI) Company	[18]
MR2	EPRB-2 miniature pressure transducer	Althen Sensors	[19]
MR3	ADIS16485 Tactical Grade Six Degrees of Freedom MEMS Inertial Sensor	Analog Devices	[20]
MR4.1	Subtillo 628i - Iridium/GPS Super Low Profile Antenna	Iridium	[21]
MR4.2	OEM7600 Dual-Frequency GNSS Receiver	Novatel	[22]
MR5.1	Subtillo 628i - Iridium/GPS Super Low Profile Antenna	Iridium	[21]
MR5.2	Iridium 9602 modem	Iridium	[23]
AR1	Nanomind A3200 OBC	GomSpace	[24]

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AR2	Nanopower P31u Electrical Power Supply System	GomSpace	[25]

All the previously presented components would be linked between them conforming the layout presented in Figure 4.

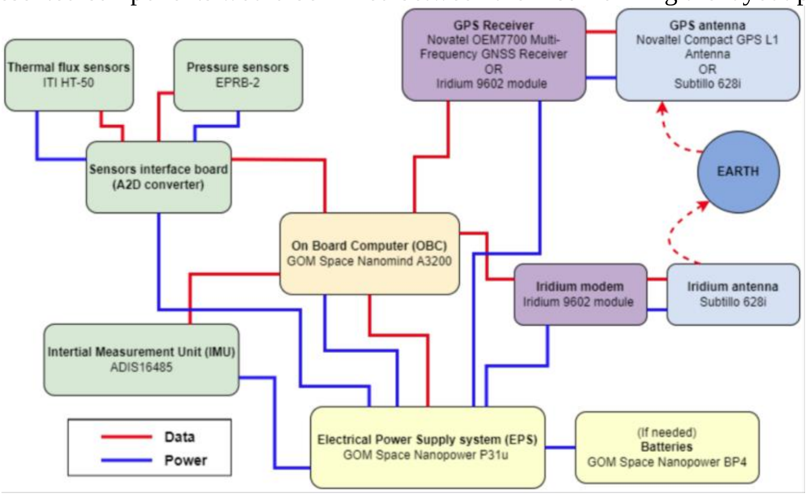

Figure 4: Payload module block diagram

Finally, a draft of CAD model was developed to verify that all these components would fit in the 1U module that is allocated for them. The result of this quick arrangement can be seen in Figure 5. In effect, all components seem to fit in the 1U payload module. However, some other points would need to be taken into account. For instance, the harness with all the cables of the components needs to be integrated in the device.

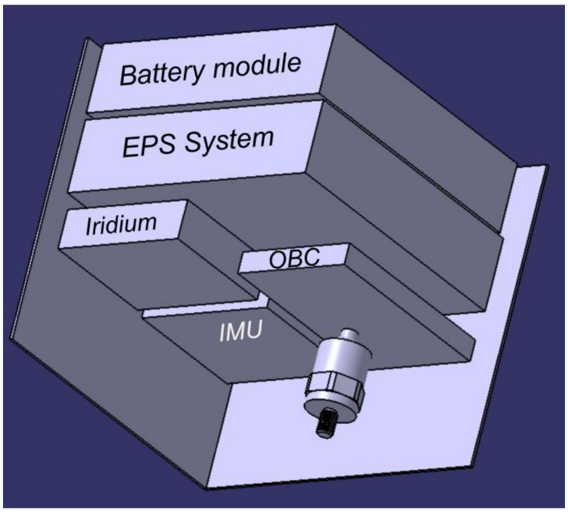

Figure 5: Physical check of clearance in 1U payload module

7. Thermal & Mechanical Aspects

The next challenge addressed was the sizing of the (Flexible-)Thermal Protection Systems (F-TPS) that are used as external heat shield of the BFS kit, as well as the internal thermal insulation of the payload. For this, a study in successive phases and levels of refinement was performed. The overall idea is to study how, starting from a given external temperature, this temperature is conducted through a F-TPS, whose internal face must be always kept below 600°C, and then heat would be transmitted to an aluminium payload, whose temperature must be always well below 100°C. For these applications, the threshold will be set to keep a temperature payload below 60°C.
The study was conducted using 3M Nextel 312 [26] for the F-TPS material, aluminium [27] for the payload material, and multi-layer insulation (MLI) [28] for the payload protection. With respect to the geometry used, the F-TPS is

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considered a truncated cone like the one shown in Figure 6, with flat small base of radius 50 mm, generatrix side of 300 mm and semi-angle of 60°. The thickness of the cone is the only free parameter left for the study.

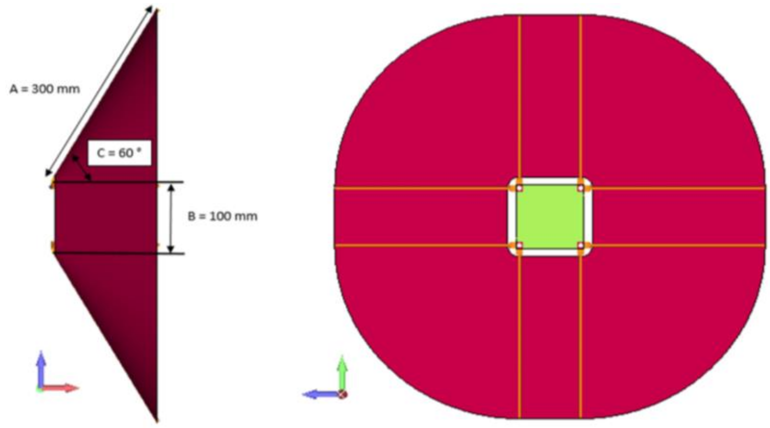

Figure 6: Geometry of the F-TPS truncated cone

Starting from Fourier's law for heat conduction, we can determine the following equation linking the thickness of the F-TPS e_{FTPS} to the internal temperature T_2, for a given constant external temperature T_1. λ_{FTPS}, S_{FTPS}, m_{FTPS}, c_{pFTPS}, T_{20}, and t represent respectively the conductivity of the F-TPS, the surface of the F-TPS, the mass of the F-TPS, the thermal capacity of the F-TPS, the initial internal temperature, and the time.

$$\boldsymbol{T_2(t) = T_1 - (T_1 - T_{2_0}) \times e^{-\frac{\lambda_{FTPS} \times S_{FTPS}}{m_{FTPS} \times c_{pFTPS} \times e_{FTPS}} t}} \qquad \textbf{(5)}$$

The first instance to be analysed is the conduction through the Nextel F-TPS to go from a constant external temperature T_1 to an internal temperature T_2 that must be kept below 600°C. The key parameter to be adjust until compliance with this requirement is the thickness of the F-TPS (e_{FTPS}). Three cases are analysed for T_1 and the total time of thermal loading:

Table 6: Results of the thermal analysis for each input temperature profile

	Temperature T_1 (°C)	**Time t_f (s)**	**e_{FTPS} (mm)**	**T_{2f} (°C)**
Case 1	1500	60	2.2	562.5
Case 2	1000	300	3.6	584.0
Case 3	650	700	3.2	598.8

With this, it can be seen that Case 2 is the most demanding one. A Nextel thickness of 3.6 mm is deemed enough to keep the internal temperature of the F-TPS at 584°C. We the geometry used, the mass corresponding to this thickness is 2.85 kg, which is a good value for the envisaged mass budget of the BFS system.
To determine the size of the MLI, the F-TPS is kept the same as in Case 2, providing the same maximum temperature T_2 = 584°C. Iterating with the size of the MLI blanket, a thickness of 4.0 mm provides an acceptable temperature of 58.9°C for the aluminium payload. Figure 7 shows the evolution of these two temperatures, keeping the final temperature always below the threshold.

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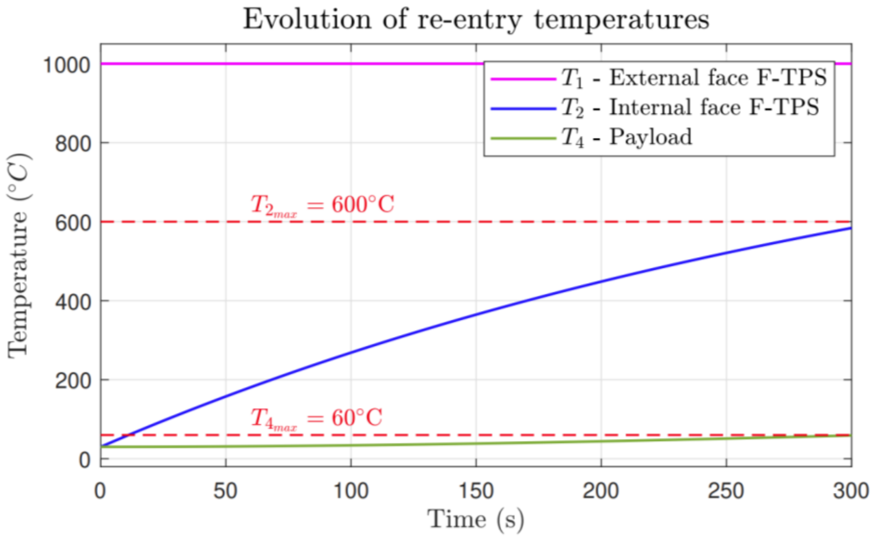

Figure 7: Temperatures for conductive F-TPS and MLI

Finally, a study was conducted to determine the size and mass of the beams holding the heatshield. The maximum surface pressure that must be withstood is of 3400 Pa. The number of beams was set at 8 and the Nitinol alloy [29] was selected for them. To determine the diameter of the beams to comply with the requirement of the tip displacement of the beam v_{bmax} = 78 mm, the following equation was used:

$$v_b = \frac{q_b \times l^4}{8 \times E \times I_y} \tag{6}$$

With q_b, l, E, and I_y being respectively the load per meter, the length of the beams, the Young modulus of the Nitinol alloy, and the second moment of inertia of the beams. Through several iterations, a diameter of 6.5 mm was found for a tip displacement of 74.01 mm. This leads to a total structural mass of 513.6 g, which is very good for the tight mass budget of the BFS system.

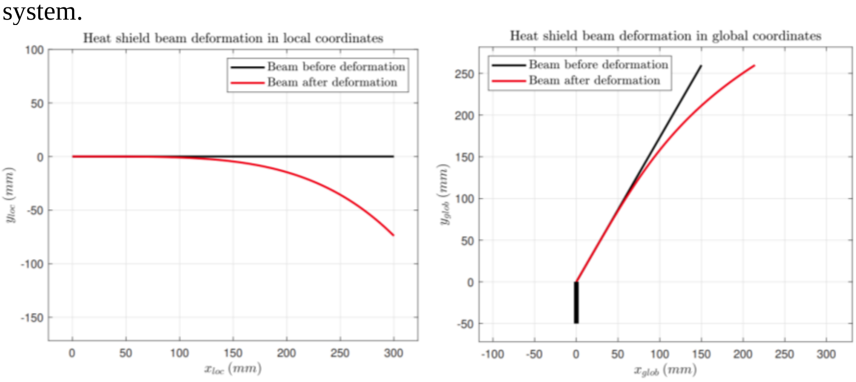

Figure 8: F-TPS Nitinol beams maximum deformation in local and global coordinates

8. Roadmap

Through the various studies conducted, we managed to define the different requirements and aspects for a possible mission of the BFS in a CubeSat size. These studies culminated with the presentation of the results in front of a jury at ISEA-SUPAERO [30] that was received with great interest. This comforted e.NOVA in the submission of the project to the 2021 CNES Call for Proposals, which could lead to an In Orbit Demonstration-In Orbit Validation of the concept in the next two years.

In addition, the study on the Nanosat size started due to a bigger potential market. The goal of this study is to adapt the BFS concept to bring back either 5 or 9 CubeSats in one bigger payload module. Different contacts have been established with companies specializing in different areas of relevance to find suitable solutions and discuss the feasibility and interest of the project. Still, with the idea of allowing the BFS kit to give ISS payloads the possibility to return more frequently, particular attention was given to the safety and the compliance with ISS safety regulation to

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all technologies considered. As such, collaborations with MECANO.ID [31] and EXOLAUNCH is being considered for the separation rings and one with Dawn Aerospace [32] is considered for propulsion. Preliminary assessment of offered GREEN propulsion and related high-pressure vessels does not fundamentally differ of what accepted in the past for SPHERES experiments allowing to suggest acceptability.
From Mission and customer point of view, good contacts have been established now with Nanoracks, SpaceMedex and recently with LOFT Orbital investigating the capability to propose the ferry back in their catalogue of services for customer's experiment embarked in their payload containers.
In addition, this concept has been found attractive by Space Pharma company who aimed to recover their laboratory or their "made in space" molecules.
Consequently, the project with a complete industrial roadmap was submitted recently to CNES Call for Project "Innovative Technologies for Nanosat" expecting a funding from the agency as kick-off starter for other entrepreneurs and business Angels.
During this process, future development is kept in mind. As such, adaptations of the BFS are being considered to offer additional services. With some small changes to its design, the BFS could also serve as a Space Tug or a Space Lab before returning to Earth and bringing its payloads back. The technology developed could also be reused in future missions to give extra-terrestrial sample containers the protections they need to reenter our atmosphere or investigated for use in exploration purpose on extraterrestrial celestial bodies.

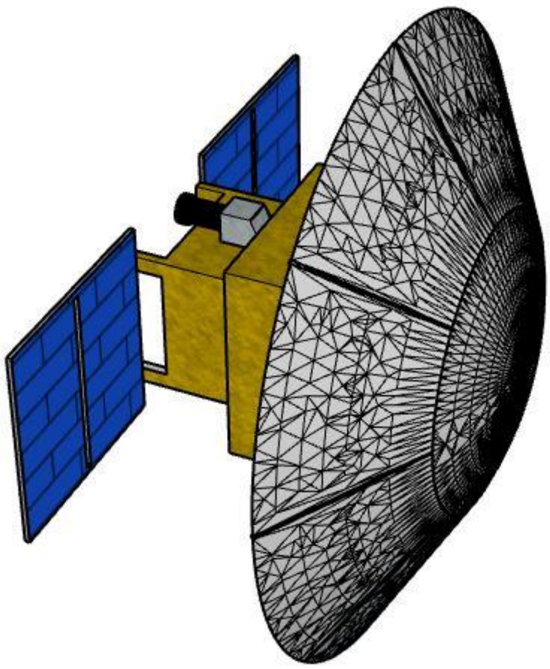

Figure 9: Preliminary BFS Heatshield CAD model

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