DESIGN, DEVELOPMENT AND TEST OF A COMPACT LIGHTWEIGHT CAPSULE RECOVERY SYSTEM

Gerrit Hausmann
Dresden University of Technology, Dresden, Germany
ghausmann@hotmail.com

Fabio De Pascale
Delta-Utec SRC, Leiden, The Netherlands
fabio@depascale.eu

Michiel Kruijff
Delft University of Technology, Delft, The Netherlands
Delta-Utec SRC, Leiden, The Netherlands
michiel@delta-utec.com

Maxim Mironov
Samara State Aerospace University, Samara, Russia
max_mironov@rambler.ru

ABSTRACT

This paper reports about the development and test of a recovery system for small capsules, originally developed for the YES2 satellite launched in 2007, that included a miniature re-entry capsule, Fotino. The system includes a beacon and parachute, an activation system, and a compact spring-based parachute ejection system, initiated by a pyrotechnic device.
Design challenges were low mass (few hundred grams), low volume (the ejection system is the size of a shoe-polish box) and (de)installation possible with minimal access. High ejection energy was required (about 15 J) to eject the parachute even reliably from a spinning fast-dropping capsule. The system can be used for recovery of lightweight capsules and probes released from orbit, sounding rockets or high altitude balloons.

The overall design approach has been hands-on, goal-oriented and pragmatic, due to time and budget constraints. Pros and cons of this approach are highlighted.

The paper reports on design, trade-offs and the successful qualification of the various systems involved and the mechanism in particular. Unfortunately the capsule has not been recovered yet, but analysis of its whereabouts and possible reasons of lack of beacon signal will be discussed. Nevertheless, a reflight is foreseen, as the successful qualification and overall mass and dimensional properties make the recovery system an attractive option for future small capsules and probes.

1 INTRODUCTION

The Fotino capsule is an innovative re-entry capsule of 400 mm diameter and a mass of only 6 kg [1] (Figure 1). Its objective is to demonstrate feasibility of such a lightweight capsule and study the aerothermodynamics in the transition regime between rarefied and continuous flow. The science data is contained on FLASH memory and would be available after landing (or crash).

In order to reduce Fotino's landing velocity for safety reasons, to about 15 m/s, a very lightweight parachute and ejection system was developed. The landing point of the capsule itself is of course also important, namely to reconstruct its trajectory, to confirm survival and to make possible recovery of the data. For this reason a beacon system was developed. Main design drivers were low mass, compactness and survival in case of crash (parachute failure). The parachute ejection system and beacon are controlled by a single electronics board which contains a pressure sensor, a timer, safety and arming wire connections (one of them triggering the timer by melting in the early re-entry) and a hardware decision logic. Together these systems are called the Primary Recovery System (PRS). This paper discusses design, integration and test of the PRS.

Fotino is the 400 mm diameter re-entry capsule of the second Young Engineers' Satellite project (YES2). YES2 was an ambitious experiment, built and developed entirely by students and managed by Dutch company Delta-Utec for the Education Office of the European Space Agency[2]. In September 2007 the project successfully demonstrated that a re-entry capsule in Low Earth Orbit (300 km) can be deorbited towards a predetermined landing area using deployment and swing (or "hurling") on a 32 km tether without the need of a rocket system and active attitude control[3], see also Section 7.

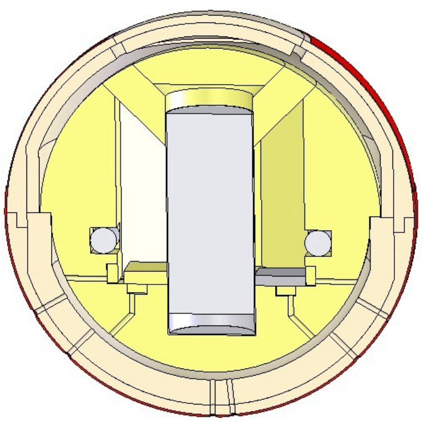

Figure 1: Section of the "Fotino" light-weight re-entry capsule revealing the central foam core (near spherical) beneath the heat shield, and the parachute cylinder set up to allow the parachute to break through the aft heat shield. The parachute ejection system is placed at the bottom of the cylinder.

The Fotino, being passenger on the Foton microgravity experimental platform and designed to land on Earth, was recognized as a potential safety hazard. For this reason, the relevant quality control and design standards were applied, and a full configuration item control, qualification (shaker, thermal vacuum) and verification of requirements was required[4]. The low cost approach and hands-on involvement of many students, which was part of the educational objective of the project, however meant that ESA standards were approached and sometimes were relaxed without compromising overall safety.

2 THE BEACON AND PARACHUTE ACTIVATION SYSTEM

The brain of Fotino's recovery system is the Beacon Activation System / Parachute Activation System (BAS/PAS). Its function is to ensure the activation of the beacon and the deployment of the parachute at the right time in flight, and at that time only.

2.1 Objective

Both the beacon and the parachute activation are designed to happen during re-entry at an altitude of roughly 5 km [5]. Both of these systems are absolutely critical for Fotino's success, and their activation is a necessary event in a successful YES2 mission.
Likewise, a premature activation of both systems carries possibly catastrophic consequences. In case of the parachute, a premature activation means the destruction of Fotino's heatshield before or during reentry, dooming it to burn up in the atmosphere. A premature activation of the beacon does not mean the immediate destruction of Fotino, but wastes precious battery power. If occurring sufficiently early as to deplete the batteries before reentry, the beacon would be rendered entirely useless, making a successful recovery of the capsule much more unlikely.

2.2 Activation Events

The integrated logic of the BAS/PAS system uses two independent sensors plus a manual arming plug to activate beacon or parachute.

The arming plug, the first and most simple of all three elements of the BAS/PAS activation, is plugged into the backside of Fotino before launch. It resets BAS/PAS, switches on the capsule power and activates the three-state logic of BAS/PAS. Also, it physically connects the parachute ejection system's pyrocutter to BAS/PAS.
Without this plug, the pyrocutter is disconnected and an accidental and possibly harmful parachute deployment is impossible.

One of the sensor elements of BAS/PAS is a pressure sensor. After the board's activation, it starts periodically measuring the air pressure inside the capsule. Once it detects an air pressure lower than that of an altitude of 5 km, it sets the BAS/PAS´s state to "space". After return to a pressure above that of 5 km altitude then, it sets the board's state back to "ground". The completion of this ground-space-ground cycle is a key element in BAS/PAS´s logic, as will later be illustrated.

The other sensor of BAS/PAS is a meltwire. Placed near the stagnation point of the capsule, it melts under the intense heat of Fotino's reentry and activates a timer in BAS/PAS.

Two additional meltwires, one placed near the stagnation point and the other near the equator, serve as additional safeties for the system. Both require to be molten for the BAS/PAS to fully arm.

2.3 Logic

Explaining the logic of BAS/PAS is best done with Figure 2 at hand. First of all, the system must be activated and physically connected to power and the parachute ejection system's pyrocutter by means of the arming plug.

BAS/PAS now periodically checks its pressure sensor and meltwire. One activation signal is the completion of the ground-space-ground cycle as indicated by the pressure sensor. The second activation signal is the elapsing of a timer, which in turn is started by the melting of the meltwire during reentry[6].
When one of these activation signals is given, BAS/PAS activates Fotino's beacon. For the deployment of the parachute however, both activation signals are required.
The difference between these activation thresholds gives justice to the different risks the systems hold in case of a premature activation.

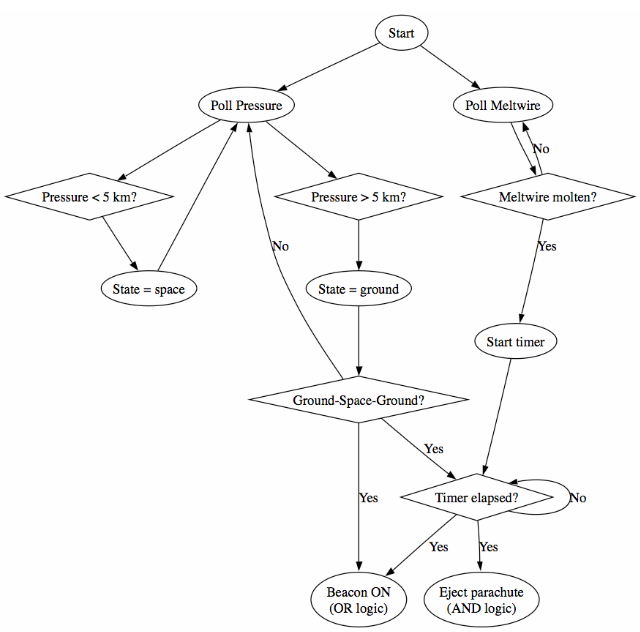

Figure 2: The beacon / parachute activation logic delivers safe and reliable function[5]

2.4 Testing

To ensure the performance of the actual BAS/PAS system, several tests were conducted. First tests of the board itself were carried out. These tests electrically simulated the performance of pressure sensor and meltwire[7].
Later system tests then actually used a vacuum chamber to simulate the ground-space-ground pressure change cycle. Both the board's logic and its outputs, such as the firing pulse for the pyrocutter, were confirmed this way[8].

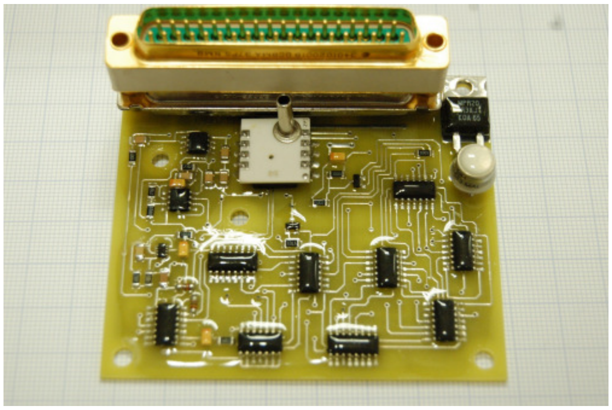

Figure 3: Beacon and parachute activation system, containing pressure sensor, timer, and logic. Meltwires, arming plug and testing equipment are connected via the connector.

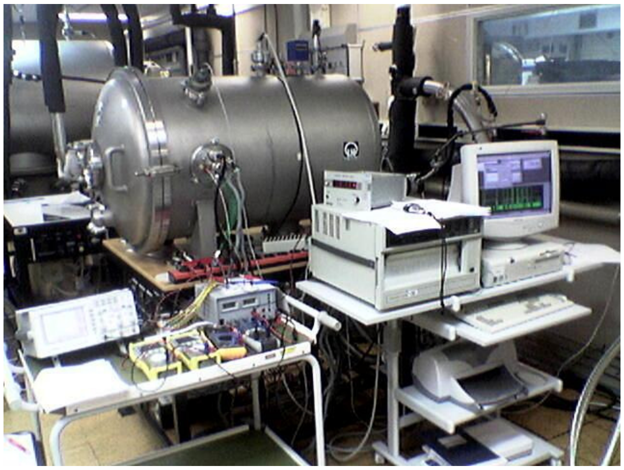

Figure 4: Set-up for BAS/PAS vacuum cycle testing

3 BEACON SYSTEM

As stated before, for Fotino's mission to be a success, it needs to land safely and make its location known to a recovery team. The latter is the job of the ARGOS beacon. The Advanced Research and Global Observation Satellite (ARGOS) system is a commercially available satellite-based worldwide tracking system. The system is a common instrument for scientific tracking of objects and wildlife all around the planet.
Its accuracy is limited to 350 m, yet this was accepted for two reasons. First, the ARGOS beacon was the smallest, most rugged and simplest satellite transmitter available. Secondly, Fotino carries a short-range homing beacon[9].

3.1 Transmitter

The beacon itself is very small and lightweight and in Fotino's case, it is programmed to emit a transmission burst every 40 seconds. Once these signals are received by one of the polar orbiting ARGOS satellites, the Doppler shift of their frequency is analyzed to estimate the signal's position. Following this procedure, the owner of the beacon is notified via Internet of the beacon's location in real time.
The beacon used in Fotino carries an independent 72 hour energy supply to maximize the probability of accurate detection of the beacon's signal by a passing satellite. A satellite pass overhead occurs at least every 3 hours. Three hours therefore is the maximum time delay expected between landing and acquisition of the capsule's position.

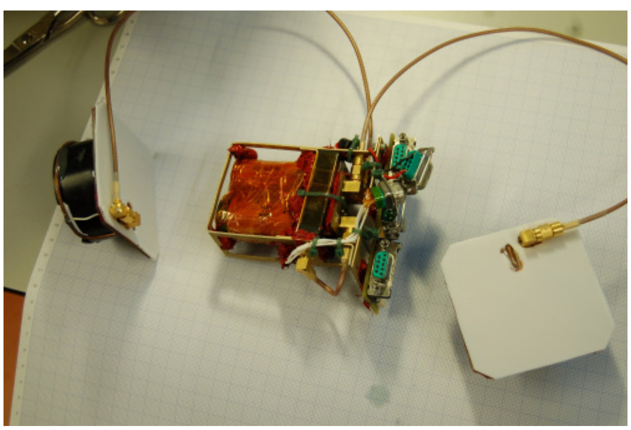

Figure 5: The complete integrated beacon system with two DDRR antennas and battery supply for three days.

3.2 Power supply and activation

In addition to the ARGOS transmitter itself, the beacon requires power supply, an electronic activation circuit and antennas.

The power supply is provided by two batteries, which are connected to the ARGOS activation board. Upon receiving the activation signal from the beacon activation system BAS/PAS, the ARGOS activation board commences power supply for the beacon. It automatically continues this power supply until the batteries are depleted.
For ground testing, a powered deactivation command can be sent by the Electrical Ground Support Equipment (EGSE).

The transmitter's signal goes directly to a splitter unit, which then passes it on to the two DDRR antennas on opposing sides of the capsule. This antenna arrangement ensures a near omnispherical signal radiation.
Both the capsule's structure and its heat shield are radio-transparent, so the antennas can be securely positioned within the capsule's body.

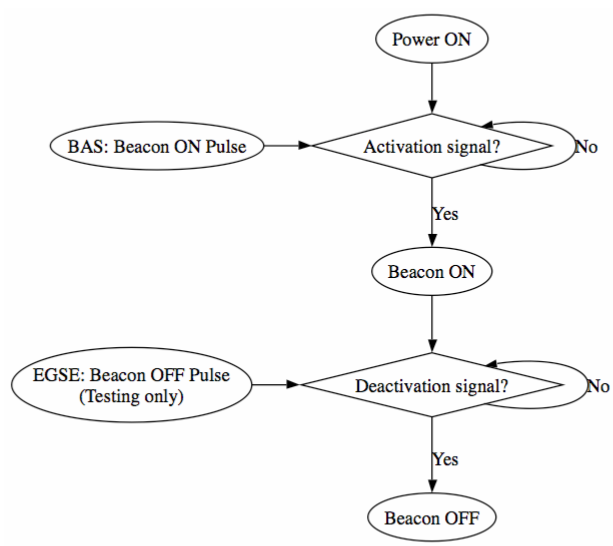

Figure 6: The Argos Activation board's logic

3.3 Crash protection

Because of the criticality of Fotino's ARGOS beacon, the entire system is hardened against impact damage. Beacon, batteries, splitter and activation board are fixed to a single protective aluminum structure[10]. This assembly, the antennas and all connecting wiring is placed outside of the capsule's central aluminum electronics holding structure (WEB) and deep inside the capsule's polyurethane (PU) foam body. Here, it is protected as well as possible from possible cable-cutting movement of other parts during a hard landing.

Note that the connection to the beacon activation system BAS/PAS is necessary only for the initial activating pulse, which will be given at the latest at an altitude of 5 km during the capsule's descent, thus well before landing. After this activation pulse, the beacon system is totally self-sufficient.

3.4 Testing

Ground testing showed successful performance of all components of the beacon system[11]. An actual flight test could not be performed, as the vacuum required as an activation event was obviously impossible to simulate.

3.5 Possible Improvement

Future missions might use a simplified and more redundant beacon system. As for simplification, first a lighter activation board without DSUB connectors is recommended. Next, it is advisable to use uncomplicated monopole antennas instead of DDRR type antennas, which proved to offer little advantage while being relatively large, heavy and difficult to integrate.
As for redundancy, it would be desirable to use two separate, fully autonomous beacon units, each with its own smaller activation board, an antenna and a smaller battery.
Reduction of the battery size would be acceptable as far less than 72 hours of signal transmission should be sufficient for successful localization by the ARGOS constellation.

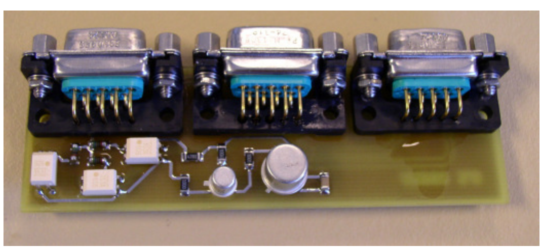

Figure 7: ARGOS activation system. Once activated, it can only be switched off by a powered command, not by severing wires to the beacon system.

4 PARACHUTE EJECTION SYSTEM

Because of its difficult task combined with numerous design limitations and high safety requirements, the ejection system turned out to be one of the most work-intensive parts of Fotino's capsule recovery system. The following section will give more detailed information about the problems encountered, the methods applied and the results achieved. Also, this section highlights possibilities for further improvement.

4.1 Boundary Conditions

As part of the Fotino capsule system, the parachute ejection system had been given a number of boundary conditions.

Mission Requirements

The parachute system was to be designed to reliably eject Fotino's parachute during the final stage of the capsule's descent to earth. Before this, it was to safely endure a several-month waiting and shipping period. Also, it could under no circumstances subject the Foton spacecraft's mission to any sort of risk[12].

Mechanical Requirements

The development was also limited towards the shape of the ejection system. The parachute system as one was assigned a cylindrical space in the center of the capsule (Figure 1)[13]. In this space, it was to accommodate both the parachute and all parts of the ejection system, whatever its final design might be. Naturally, the space finally available for the ejection system was then defined by taking the parachute system's space allotment inside Fotino and subtracting the space required by the folded parachute and its containing sabot.
Also, the parachute system was required to supply the parachute with a sound connection to the capsule itself, transferring (and dampening) the decelerating force produced.
The parachute system as a whole was allowed a mass budget of 450 grams, roughly 230 of which were taken by the parachute and its accessories.

Electrical Requirements

The design of the parachute activation system was such as to activate the ejection system with an electrical pulse (at least 1.5 A for at least 100 ms). Whatever mechanism the ejection system was to employ, it would have to accept this signal.

Organizational Requirements

Inside Fotino, the parachute system would be in the center of the capsule, surrounded by the electronic equipment. It would be filling most of the space there. To allow integration and connection of the electronic equipment, the parachute system would have to be the last part integrated into Fotino. As such, it had to be designed for easy in-capsule integration with access only from the top.

In case of a detected failure of one of the installed subsystems, the parachute system would also have to be removable.

Apart from that, there were more safety requirements. Of course, danger-free operation was not only required in a large scale concerning the Foton carrier spacecraft, but also on the small scale concerning personnel and equipment during integration. Whatever form the ejection system's energy source might finally be in, it would have to be fully contained and controlled at all times.

4.2 Methods

Naturally, the requirements given above left ample room for creativity, beginning with the simple question of how to store the ejection system's energy. Next came the question of how to release this energy, how to facilitate force transfer to the capsule, integration, assembly, activation, and so on. Figure 8, while hardly readable, offers the variants discussed only for the three major points of the later investigated system relying on spring-stored energy, thereby illustrating the encountered complexity.

To get an effective grip on all the different variants available, several methodical approaches were applied by the YES2 team.

First basic simplification

To drastically reduce the number of possible variants right in the beginning, the first decision undertaken in the ejection system's development was that of the energy storage to be used. As the team was evenly split between supporters of an ejection system based on a hot gas generator[14] and those of a spring-based system, basic prototypes were projected for both. They were then compared in detail using a simplified benefit value analysis, in which the hot gas generator was seen more favorable than the spring system it all aspects but safety (see Table 1).

Open safety issues here included flying debris, electromagnetic interference, influence of moisture and fire. Qualifying such a system for flight would have required a huge safety analysis, the time for which was simply not available.

Consequently, the hot gas generator was rejected and all further development was focused on a spring-based parachute ejection system.

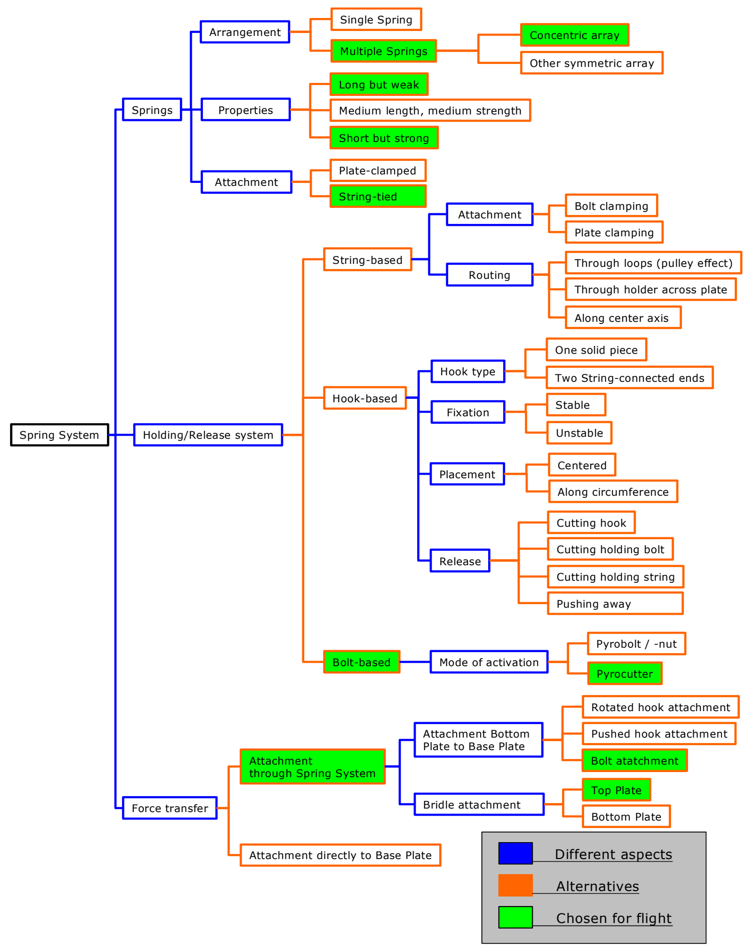

Figure 8: Even for such a seemingly simple subsystem as the spring ejection system, there quickly was a whole multitude of variants. A well structured development process was needed to cope with this.

	Gas Generator	Spring System
Mass required	-	--
Space required	o	o
Available knowledge	o	-
Cost	+	+
Manufacture and Integration	+	-
Safety	! -- !	o

Table 1: Evaluation of the two ejection principles considered

The Development Loop

For the development of the ejection system, a team member was assigned to it full-time. Ideas were developed by this person alone or in

discussion with other members of the YES2 team. Whenever an idea had solidified, it was discussed together with the Fotino manager and, whenever possible, the YES2 lead engineer. Ideas approved by discussion were then visualized in more detail with CAD software. If this also did not reveal any problems, a prototype was developed and tested.
Based on the test results, this loop was then repeated.

Incremental increase in Complexity

The level of the development's complexity was stepped up with every iteration cycle. While at first fundamentally different energy storage and release systems were investigated, later analysis revolved around how exactly to facilitate, for example, optimal bridle storage.
The same increase of detail was the case for the tests, which went hand in hand with the development on the drawing board. First experiments of the spring system were conducted with rudimentary wood and string constructions, while later ones relied on delicately milled high-quality Aluminum hardware.

4.3 Test campaign

The time available for the development of the ejection system was very limited, too limited to achieve extensive theoretical understanding of all the dynamic parts involved. For this reason, a highly empirical development process was chosen, in which the test campaign was an integral part.

For the same time limitations, the test campaign itself was limited to the bare minimum as well. Prototypes were never produced in more detail than absolutely necessary, the first consisting only of wood and string.
Also the number of tests for any given combination of prototype and test condition was limited to three, as this was seen at the smallest number of tests required to receive reliable results. All in all, 17 tests of the spring system were conducted during its development[12].

Investigation of force and friction tests relating to the parachute's exiting of the capsule as well as of possible flight conditions during reentry had resulted in a given minimum kinetic energy for the parachute. This energy value, including safety factors and converted into a value of potential energy, gave a required ejection height of 2 m against gravity. Therefore, ejection tests were conducted with the parachute being ejected upwards against earth's gravity, and the ejection height was used as the systems´ benchmark.

In order to avoid interference with the ejection height achieved all parachute ejection system tests were conducted in a controlled environment without air currents or limiting objects.
The tests were recorded by videotape. Meter bands were located near the test setup for scale on the video recording. Pre- and post test conditions were also videotaped and, when appropriate, photographed (Figure 9). Doing so allowed later analysis and proper reporting.

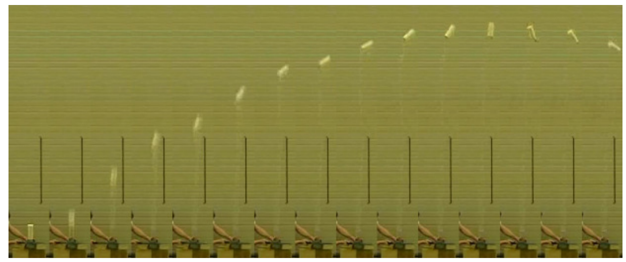

Figure 9: Parachute ejection sequence, the images are equispaced by 1/25 s (total sequence 0.6 s). The black line is 1 m long.

4.4 Result

The resulting ejection system (Figure 10) consists of two concentric springs mounted in between two thin Aluminum plates. After compression, these plates are held together by a central bolt, which passes through a pyrocutter.
Tests confirmed this system's reliable performance in breaking the parachute through the capsule's heat shield and ejecting it over the required two meters in height against earth's gravity.
Its final mass is 282 grams, the parachute system as a whole thereby exceeds its total mass budget by 62 grams. The parachute system still was accepted for flight inside Fotino, as no immediate spots for mass reduction could be found, and as there was no time for elaborate improvement.

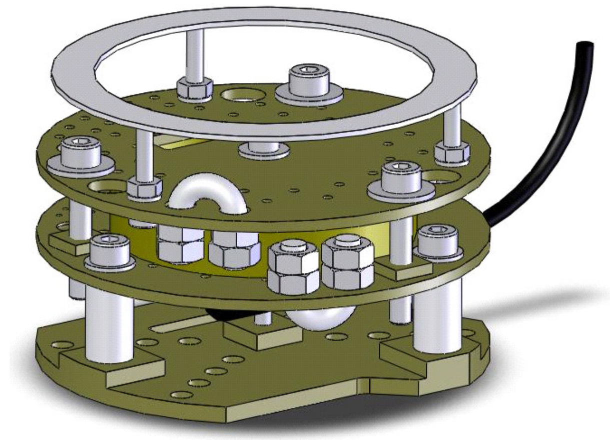

Figure 10: CAD model of the flight spring system

General function

Upon receiving the electric activation pulse from the parachute activation system, the charge inside the pyrocutter fires, cutting the central bolt in two. This releases the springs from their compressed position. The inner spring, shorter but far stronger than the outer spring, breaks the sabot-contained parachute through the capsule's pre-perforated aft heat shield. The longer outer spring then provides the long thrust throwing the sabot with the parachute out of the capsule. The bridle, loosely coiled on the ejection system's top plate, unravels and allows the distance between parachute and the capsule to build up to its full length of 3 m. Upon hitting the 60 m/s air flow[5] around the capsule, the sabot's two halves separate from the parachute, which then unravels and opens.

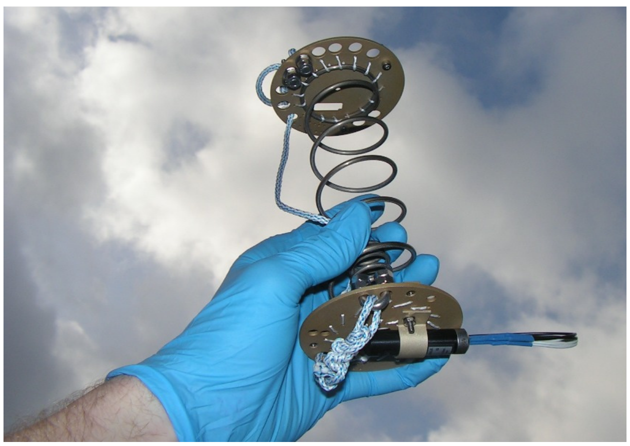

Figure 11: The parachute ejection system with unloaded springs. The central short spring is to break the capsule heatshield, the long spring then accelerates the chute away from the capsule

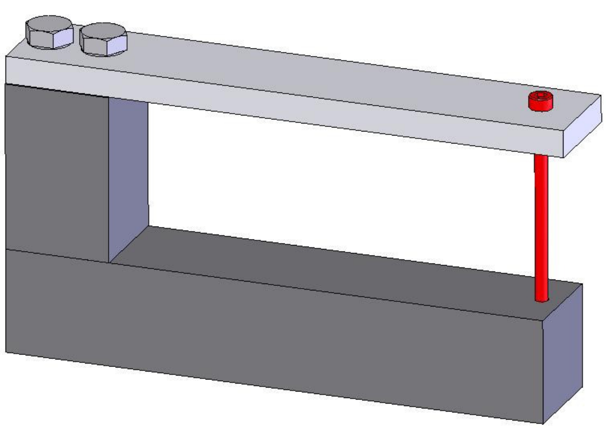

Figure 12: The pyrocutter test bolt pretensioning device. The pretensioned bolt is marked red.

The opening shock, i.e. the initial peak drag force of the parachute after opening, is transferred through the bridle into the ejection system's top plate, and then via the long spring into the system's bottommost plate, the base plate. The long spring deforms plastically, acting as a shock absorber. After reaching twice its original length or in case of breaking, the long spring's connecting function is taken over by a safety line.

The base plate transfers the parachute's force to the capsule's core by two means: First, by the silicone with which it is glued directly to the core, and second through four anchors at the outside of the core (Figure 18).

Release System

Perhaps the most difficult part in the development of the ejection system was the holding and release system. How could the force of the compressed springs - almost 400 N - be safely held and then easily released by the most simple and fail-safe system possible? And how could this system be activated by the Parachute Activation System's electrical signal? Many variants using strings, hooks, levers and electric motors were discussed. The flight solution finally surfaced when a stronger pyrocutter came to be available.

Immediately, there was the idea of fixing the compressed springs in place with a single bolt and, for release, using a pyrocutter to cut that bolt.

While the pyrocutter used was originally designed to cut wires and not bolts, consulting its manufacturer indicated that, based on previous experiments, cutting an M3 bolt should not be a problem. To prove this hypothesis, a test was conducted, in which a bolt similar to the flight bolt was pretensioned to the load of the compressed spring system (Figure 12). This bolt was cut by the pyrocutter reliably, and the pyrocutter / M3 bolt combination was considered flightworthy.

This test was very convincing of the used pyrocutter´s ability to perform YES2´s unusual application, but at least two more repetitions of this test are recommended in case of the ejection system's further use. Due to a shortage of pyrocutters combined with long delivery time and bureaucratic hurdles, such a test program was not possible during the ejection system's development.

Spring Selection

The first approach to selecting the parachute system's springs was energy-based. The value needed for a worst-case ejection energy was known, and a compressed spring's energy could easily be calculated assuming a linear spring coefficient:

$$F(x) = c \cdot x \quad (1)$$

$$E = \int_0^{S_N} F(x)dx \quad (2)$$

$$E = \frac{c}{2} S_N{}^2 \quad (3)$$

with F = spring force
c = linear spring coefficient
x = compressed length
E = maximum storable spring energy
S_N = maximum compression

An array of different springs was now preselected and obtained.

Later tests proved that ejection with the preselected springs was possible, but that the purely energy-based evaluation initially conducted was insufficient. Given two springs with equal energy storage but different length, there is a difference in ejection capability. Additional analysis is recommended for further development of similar systems.

The outcome of the test campaign was a selection of a concentric combination of a short and strong 4 Joule spring combined with a large and weak 10 Joule spring.

Shock absorption

In the spring ejection system, the parachute's bridle is stored coiled up on the top plate. This combined with the desired mode of ejection does not allow for rip-stitching of the bridle, and so a standard way of dampening the parachute's opening shock is unavailable.

To compensate for this, the ejection system uses its long spring as a shock absorber. The parachute's bridle is not directly connected to the capsule's core, but only to the ejection system's top plate. From here the opening shock travels through the spring to the lower, capsule-mounted parts of the ejection system. In case of very high peak forces, plastic deformation of the spring absorbs this energy. In case of failure of the spring or its attachment, a safety line takes over the spring's connecting function.

Many standard parts

The final ejection system relies heavily on commonly available parts such as nuts, bolts and hooks. This integrated concept certainly holds mass disadvantages over an integral system, but makes for much easier production as well as it allowed easier and faster modification of the system during the development process.

4.5 Assembly / Integration

As stated before when presenting the boundary conditions, the spring system was required to be the last part integrated into the capsule. However, the anchors for transferring the parachute's force to the capsule's core had to be installed as one of the first parts. Tying these anchors, consisting of Kevlar bands with aluminum end plates, to the ejection system would be impossible in the limited space after Fotino's electronics integration.

Anchor preparation

To cope with this situation the ejection system was designed so that its bottommost plate, the base plate, would be installed together with the anchors at the very beginning of the capsule's integration. Because of its flatness, the base plate does not obstruct the following electronics integration.

Assembly and charging

As a preparing step for the remaining installation of the ejection system, both springs are mounted to the bottom plate[15]. The long spring is also mounted to the top plate. Then all hooks and bolts are added to the assembly. Also, the pyrocutter is mounted underneath the bottom plate's center hole. When all this is done, the ejection system is compressed in a large vice and, once compressed, it is secured in its state by three temporary bolts around the circumference of the plates.

Insertion

This step is the last before closing the capsule, when only from-the-top access is available. First, the parachute system's barrel is inserted. Second then, the main part of the ejection system, the compressed springs with the pyrocutter, is inserted from the top into the barrel. Using a long screwdriver, the inserted part is bolted to the anchoring base plate in three places.

Next, the center bolt, the heart of the holding and release system, is inserted and also fixed to the anchoring base plate. Note that when inserted, it automatically passes through the opening of the pre-mounted pyrocutter. With the center bolt now

in place, the temporary bolts are removed. The springs´ force is now held by the center bolt only.
Following this, the pyrocutter is electrically connected to the parachute activation system, and bridle and sabot-contained parachute are inserted on top of the ejection system. The parachute system is ready for flight.

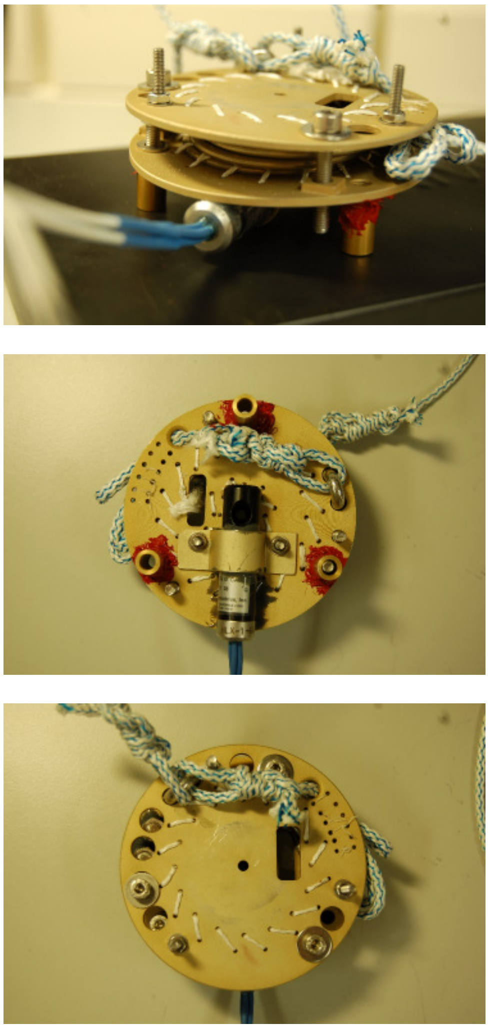

Figure 13: Different views of the charged flight parachute ejection system with pyro. The springs are held in place by three temporary bolts around the plates´ circumference. The springs force causes elastic deformation visible to the naked eye, highlighting the minimalistic use of material.

5 PARACHUTE

The parachute itself is of hemispherical type and has a diameter of 1.1 m. It is made of Nylon F111, which is a common material for manned parachutes[5].
Added by ESA requirement, it is designed to slow the Fotino capsule down from its terminal velocity of about 60 m/s to a safe landing velocity of 15 m/s [16]. The performance of the parachute has been proven by drop tests conducted by the Russian part of the YES2 team[17].

Unlike parachutes normally used for human jumps, Fotino's parachute uses a netting instead of the normal lines for suspension. This results in more material and as such more mass and volume, but avoids the danger of line entanglement upon deployment.

The parachute's flight folding was developed empirically based on the parachuting experience of one YES2 team member, and involved at least triple testing of each variant considered.
The folding finally was chosen for its optimum combination of small volume and rapid, proven opening after deployment.

Figure 14: Fotino's parachute. This photo has been edited to hide phone number and e-mail address. Reward and instructions in Russian and English serve as a last ditch recovery system backup.

6 INTEGRATION

Integration of the beacon and parachute system is best explained in the following photo series[18].

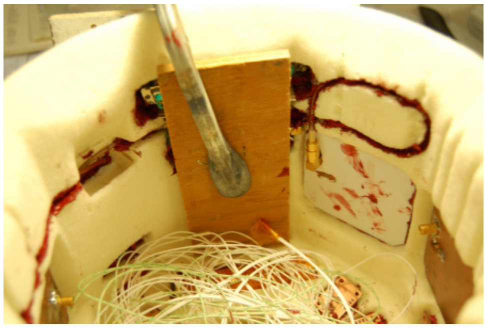

Figure 15: First, the beacon package is mounted, using red silicone as glue. It is located entirely outside the metal cage of the capsule electronics and close to its antennas. This insures maximum survival probability in case of a capsule crash.

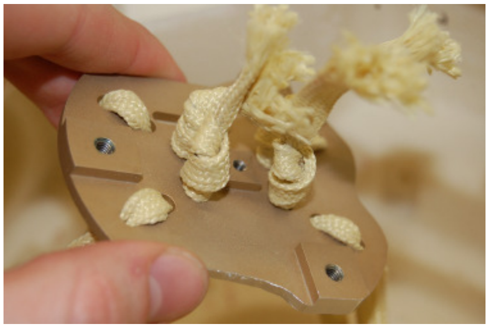

Figure 16: This is the base plate that is mounted to the bottom of the foam core of the capsule. It allows the parachute system to be mounted (and unmounted) at a late stage in the integration. The bands lead to the four anchors on the capsule's outside.

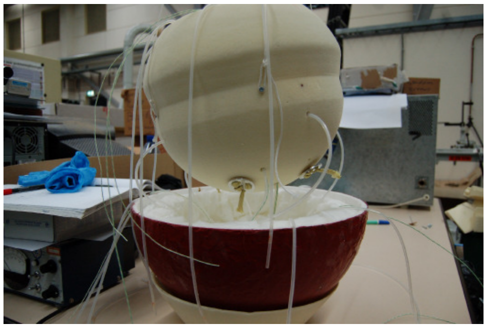

Figure 17: The base plate is anchored through four circular metal plates distributed over the PU foam core (dangling over the heat shield in this image). Note: the hoses belong to the pressure sensors in the capsule's science package.

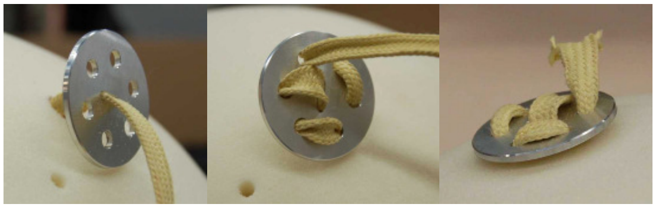

Figure 18: Close-ups of the fixation process of one of the anchor plates. Anchoring across the compressible PU core will also help to reduce the shock of the parachute opening.

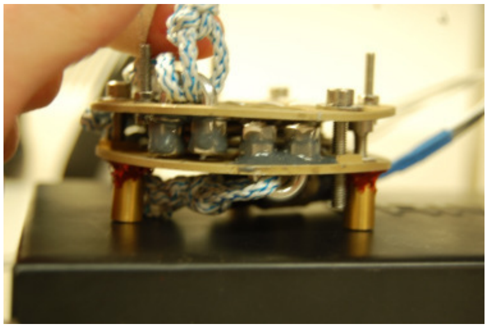

Figure 19: The compressed ejection system (elastically deformable to save mass), with anchoring of the parachute bridle. The bolts keeping the two plates together are temporary. The bottom plate can be mounted to the base plate with from-the-top access only.
The connecting bolts are inserted through holes in the top plate and pass through the golden spacer tubes into the threads on the base plate.

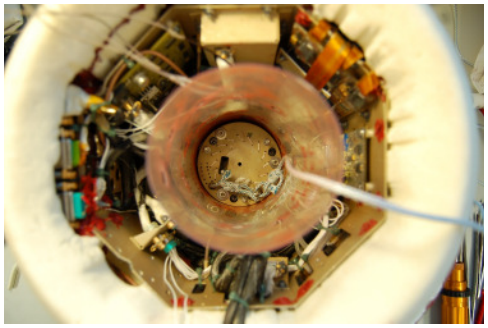

Figure 20: After integrating the electronics, the ejection system is placed inside the PET cylinder. It is mounted on top of the base plate by the connecting bolts mentioned above. Following this, the center bolt is passed through the pyrocutter and fixed into the base plate. Now the three temporary bolts are removed.

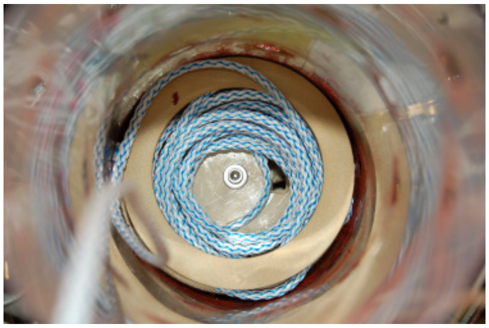

Figure 21: The parachute bridle is neatly tucked away inside a ring between the parachute sabot and the ejection system. Also clearly visible in this image: the head of the center bolt.

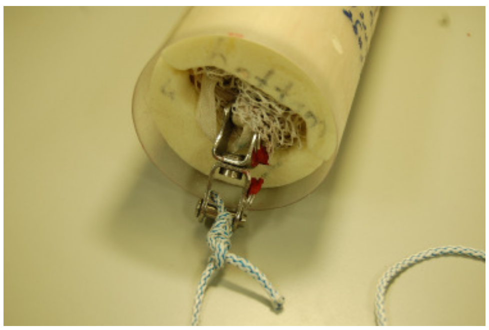

Figure 22: The parachute is folded and placed inside a foam sabot and stored in a PET cylinder. The bridle is connected to it by a swivel system to decouple parachute and capsule spinning.

Figure 23: The parachute is transferred into the capsule's PET cylinder

Figure 24: The capsule is closed

7 <u>YES2 MISSION</u>

Telemetry from the orbital platform YES2 carrier spacecraft Foton allowed the reconstruction of the capsule's earthbound deployment on the tether, as well as that of the 32 km tether itself[19].

While differing from nominal deployment (Figure 25), analysis showed that the release itself occurred as planned and that the deorbiting hurl on Fotino was successfully performed.

Data from the tethered sub-satellite MASS (which accompanied Fotino at the bottom end of the tether) allowed to estimate the capsule's heat flux and stability during reentry – both seem to have been within limits.

Nevertheless the signal from Fotino's ARGOS beacon was never received by the ARGOS constellation.

The reason for this remains unknown to this date. The capsule may have burnt up during reentry. It may have crashed with destruction of antenna cables or a power line from the activation board. Transmissions before such an impact may have been blocked by charring during reentry (Figure 27).

Also, Fotino may have made a water landing, a situation for which it was not equipped (Figure 26).

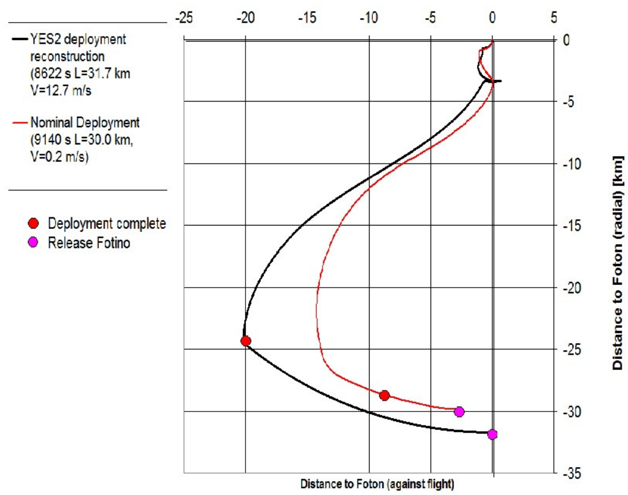

Figure 25: Trajectory of MASS/Fotino during deployment on the YES2 tether. Red = nominal, Black = YES2 flight result. View in local horizontal, local vertical, with respect to Foton. Orbital direction is left, Earth is below.

Figure 26: Estimated landing area of Fotino. Several bodies of water are proximate, so a wet landing may have occurred. The ground station was located too far upstream (over the horizon) to receive any telemetry.

Figure 27: Fotino heatshield model after re-entry test in Plasmatron[20] appears charred and could have possibly blocked the ARGOS transmission signal. Conductivity measurements made on the charring seem to indicate likelihood of such a blockage is small.

8 CONCLUSION

A Primary Recovery System has been developed and tested for use in small probes or capsules, e.g. for re-entry or drop from high altitude balloons. Unfortunately the performance in the YES2 mission could not be evaluated, possibly due to a water landing. The system is extremely compact and lightweight, yet has a triggering based on reliable logic (involving air pressure and altitude) and pyrotechnics, and includes a 14 Joule ejection energy for the parachute. In the Fotino capsule this energy was used to break through the heat shield, so no door or additional mechanism would be necessary. The tested parachute allows a deceleration from supersonic speeds to about 15 m/s in case of the 6 kg capsule design. The beacon system uses the ARGOS constellation to determine the landing site within three hours and 350 m accuracy. The system is designed to even allow recovery in case of capsule crash when the parachute system fails. A waterproofing of the system and some simplifications on the antenna system combined with a redundant beacon are recommended to increase recovery probability.

ACKNOWLEDGMENTS

We would like to thank all the members of the YES2 team for their incredible effort in making a dream come true. Whether you sat in an ESTEC office beyond midnight writing a design report or whether you conducted parachute tests at the river Sok in sub-zero temperatures, your enthusiasm and dedication was incredible. It was an honor to work with you.

Also, we would like to thank our friends and families for supporting us when we had little on our mind but work.

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