INTERMEDIATE EXPERIMENTAL VEHICLE. JETTISON MECHANISM ENGINEERING AND TEST

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ABSTRACT

The IXV (Intermediate eXperimental Vehicle) is a project of the European Space Agency that aims to develop an autonomous atmospheric re-entry system. A flight model has been launched on a Vega rocket on the 11th of February 2015 and after descending from an altitude of 420km splashed down in the Pacific Ocean.

In the frame of this project RUAG space has developed the entire cold structure and the mechanisms able to eject the panels closing the parachute and floatation balloons bays. Panels ejection allows respectively parachutes deployment, reducing the IXV re-entry speed from Mach 1.5 to few meters per second just before the splash down, and buoyancy balloons inflation which let the vehicle float on the sea surface until arrival of the recovery ship.

Such panels and the relevant mechanisms had to be designed not only to guarantee the correct external aerodynamic shape needed for the flight performance, but also to provide enough stiffness and strength to the IXV structure, being capable of transfer high shear loads.

Moreover the floatation doors design enclosed both the hold down and release mechanism, based on a non-explosive separation nut, and the jettison springs, therefore particular attention had to be put to prevent any damage to the panel during the release which could have potentially led to jamming of the panel itself which jeopardise the floatation balloon deployment. The chosen design was therefore based on a spherical joint, so that shear load can be withstand and bending moment on the jettison-able panels limited at the same time.

Test activities have been performed at mechanism level for environmental and preliminary functional qualification, subsystem level, including dummy panel jettison and full scale IXV drop test, to complete the functional qualification and system level test to close qualification campaign.

The purpose of this paper is to present the mechanism design and the activities performed to qualify at component and sub-system level the jettison mechanism of the floatation balloons doors.

1. IXV COLD STRUCTURE AND MECHANISM DESIGN

The IXV airframe is based on a hot-structure/cold-structure arrangement. The outer surface (hot structure) consists of advanced ceramic and ablative thermal protection materials which are able to withstand the severe re-entry environment and guarantee the integrity of the structure.

The inner elements (cold structure) consist of CFRP sandwich panels, providing the necessary strength and stiffness to resist the extreme mechanical and thermal loads experienced during launch, re-entry, parachute deployment and landing.

The monocoque design, depicted in *Figure 1*, is based on a low number of large CFRP sandwich panels (the so-called aeroshells) and was introduced in the C2-consolidation phase with the aim of significantly improving the structural efficiency in terms of stiffness vs mass and reducing production lead time.

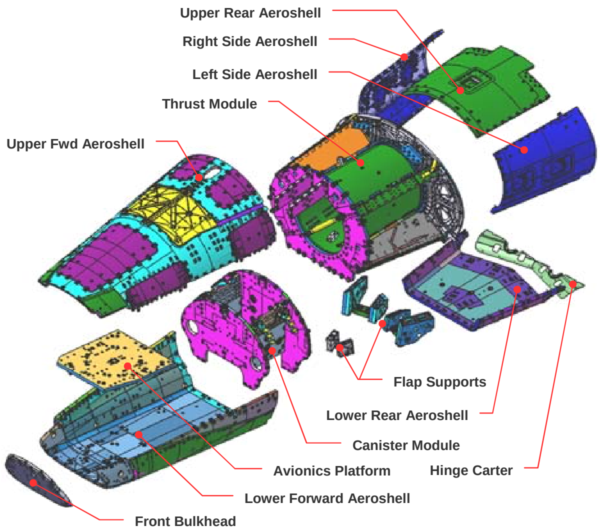

Figure 1. Monocoque design concept

To allow for the deployment of the parachutes needed for vehicle deceleration and to guarantee the possibility of floating after splash down by use of inflatable buoyancy balloons, five ejectable panel have been implemented in the upper forward aeroshell, respectively one parachute panel and four floatation panels (see *Figure 2*).

Because of the chosen monocoque design concept the panels have to bring stiffness and strength to the cold structure, therefore the "in plane" loads at mechanism level are considerably high. In addition the mechanism shall be able to cope with the alignment requirement linked to the establishment of a smooth aerodynamic shape and shall guarantee the capability of release the panel under electrical signal provided by board computer.

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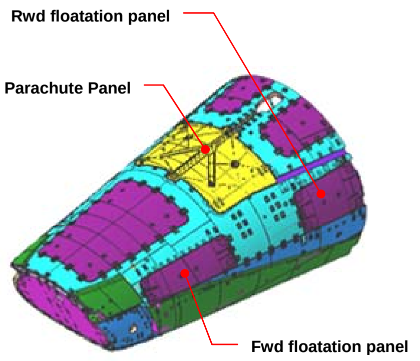

Figure 2. Parachute and floatation panels location

The design therefore has to include shimming capability to compensate steps between panels and cold structure and shall be able to deal with angular misalignment without overloading the panel by means of the implementation of spherical joint concept.

Finally for the floatation panel the design has to include means to provide the energy needed to eject the panels whereas the parachute panel was extracted by the supersonic pilot.

The main requirements for the two panel types are summarised in the table below.

Requirement	***Unit***	***Floatation panel***	***Parachute panel***
Shear QS load at separation I/F	kN	12.3	4.7
Random loads envelope (1)	g_{RMS}	26.3 (3σ)	25.7 (3σ)
Sine loads envelope (1)	g	8.1	6.3
Temperature range (2)	°C	-100 ÷ +135	-100 ÷ +135
Min. Panel ejection velocity	m/s	2.0	-
Reliability (3)	-	$1\text{-}7{\cdot}10^{-5}$	$1\text{-}2.5{\cdot}10^{-5}$
Mass excluding panels (4)	kg	27	

Table 1: Mechanisms main requirements summary

Notes: (1) presented values are the maximum among X, Y and Z direction.

(2) envelope of non-operative and operative temperatures

(3) for floatation panel reliability of single panel

(4) total mass of floatation and parachute mechanisms including mechanism frames

The floatation jettison mechanisms are based on a spherical joint secured by a G&H Separation Nut. Upon release of the separation nut, the preloaded separation spring actuates the mechanism bracket. As shown in *Figure 3* for each floatation panel 4 mechanisms are used. The mechanisms are integrated into frames installed in the cold structure to provide support the floatation balloon canister in case the upper forward aeroshell is lifted off with the canisters already integrated. Two micro-switches per panel provide a feedback about correct panel separation. The mechanism design is depicted in *Figure 4*.

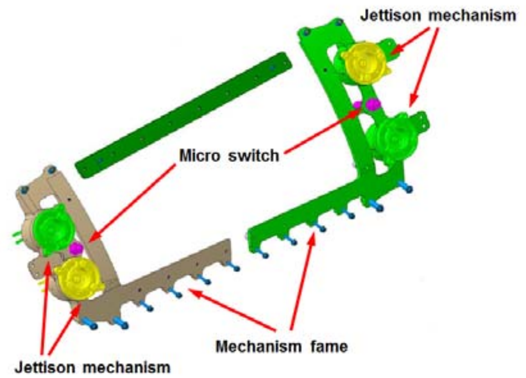

Figure 3. Floatation mechanism layout

The spherical joint, based on sphere / cone contact ring and spherical washer assembly with coincident rotation centres, ensures the compensation of manufacturing tolerances with respect to planarity of the mounting I/F, eliminating the need for wedge shims during integration which can be replaced by parallel shims. Moreover this joint minimises the bending moment transferred to the ejected floatation panel due to potential time scatter in the activation of the Separation Nuts which can lead to panel rupture and therefore potential jamming issue.

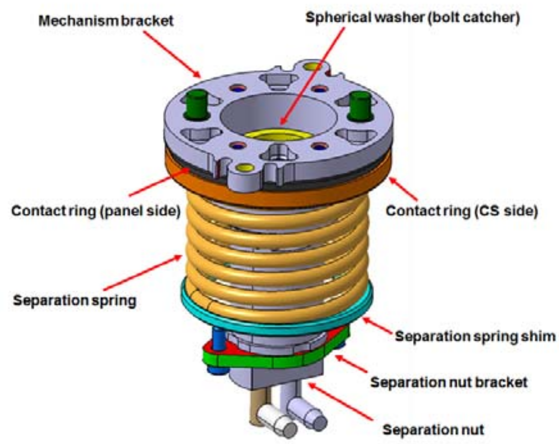

Figure 4. Floatation mechanism concept

Additionally, a bolt catcher is integrated into the spherical washer assembly with the aim of extracting the separation bolt once the separation nut is activated avoiding potential bolt jamming issues.

The separation interface is made of hardened steel A440C with Balinit C coating and Dicronite DL5 lubrication whereas the mechanism bracket and frames are made of Aluminium alloy 7075.

When the separation bolt is not mounted, the separation nut is held in place by a bracket in the rear part. To prevent rotation during mounting of the Separation Bolt, a square profile is machined into the front face of the Separation Nut and is engaged into a square housing machined in the cold structure frames.

Ageing process is performed on the separation spring to guarantee spring performances stability over time.

For the parachute six mechanisms has been used, one at each panel corner plus 2 in the centre of the panel to provide the stiffness and strength needed to withstand the re-entry loads. Mechanism layout is depicted in *Figure 5*.

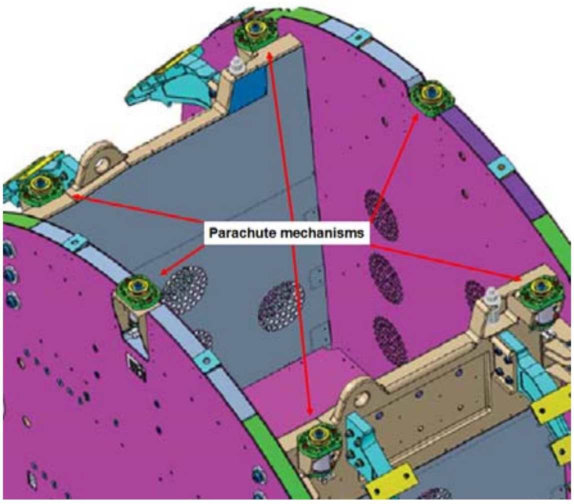

Figure 5. Parachute mechanism layout

Parachute mechanism design concept, shown in is similar to floatation mechanism with the only difference that springs have been removed since the panel is ejected by the supersonic pilot. Moreover, being the separation nuts activated when the parachute is extracted the spherical joint is used only to compensate the misalignments at the interfaces.

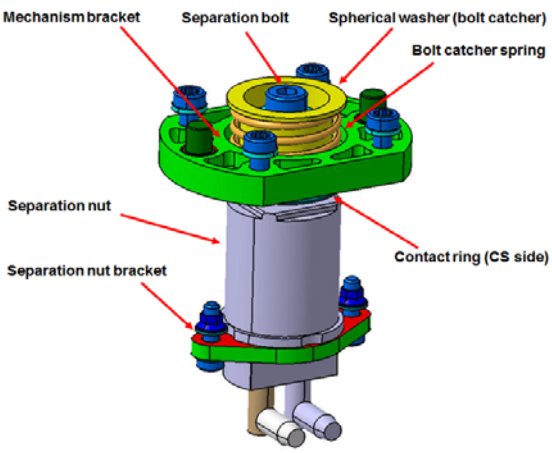

Figure 6. Parachute mechanism concept

Besides standard analysis relevant to mechanical stiffness and strength, non-linear analysis to check separation interface ring stresses due to contact pressure and separation bolt preload change linked to thermal environment, in particular at high temperature, have been performed. In the analysis the environmental loads have been applied in steps, i.e. thermal first, then mechanical axial load and finally mechanical shear load. The figure below shows the bolt preload variation for the floatation mechanism. Overall preload variation is about 7%. Similar values have been found for parachute mechanism.

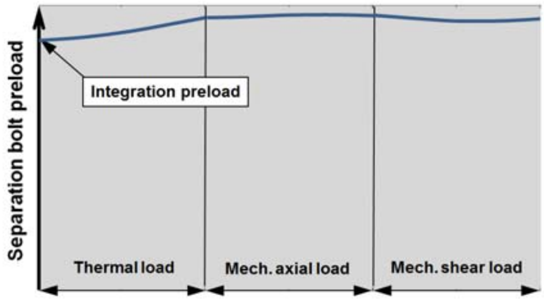

Figure 7. Separation bolt preload variation

Moreover a detailed dynamic analysis has been performed to identify the panel rotation due to mechanism opening time scatter. Target of this activity was to verify that the gap foreseen between panel and cold structure was enough to prevent jamming of the panel within the sandwich honeycomb. Starting from probability density function of a single separation nut the cumulative probability of having 4 or 6 separation nut open within a certain time scatter has been computed. On the basis of the reliability target the acceptable time scatter has been defined and panel movement calculated.
As an example in *Figure 8* the out of plane displacement versus time in case 3 floatation mechanism are released whereas the fourth is still closed is presented.

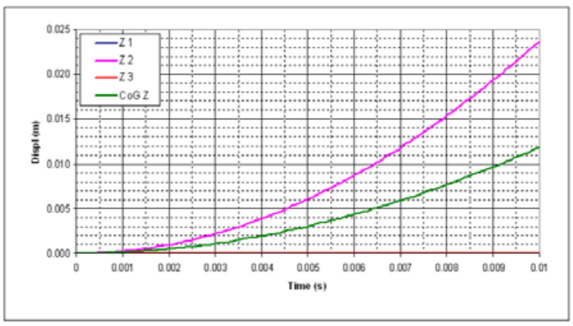

Figure 8. Front floatation panel corners displacement

The analysis has been repeated for all the combinations of open / close mechanism and corresponding rotations calculated.
On the basis of such rotations by using the CAD models it has been verified that the foreseen gap between panel and cold structure was sufficient to prevent panel

jamming. Furthermore, as a risk mitigation measure, “bumpers” have been implemented at certain locations between panels and cold structure.
Analysis has been executed as well to check that bolt catcher was able to completely extract the separation bolt from the separation nut before the contact rings were disengaged. In *Figure 9* it is presented the result of the analysis for the floatation panel. The bolt is extracted from the nut in 5ms.

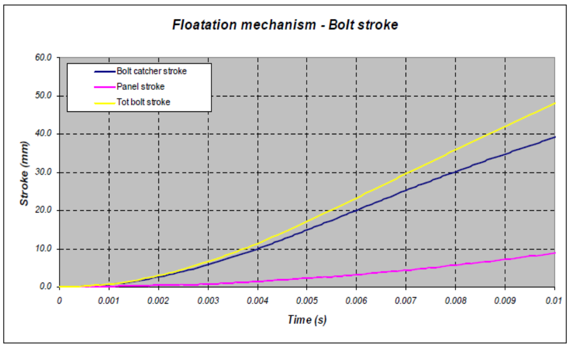

Figure 9. Separation bolt dynamic analysis

At the end of the engineering phase all the requirements have been met with the only exception of the total mass which was 31.7 kg. The mass out of spec was due to increased mass of floatation mechanism frames linked to bigger jettison springs needed for compensate panel increased mass. This modification impacted frames design not only in mechanism housings but required also some modifications in the nearby areas because of thermos-elastic stresses due to thermal expansion mismatch with respect to carbon fibre composite aeroshell.

2. MECHANISM TESTING APPROACH

The mechanism design has been qualified via a test campaign at single mechanism level following the test flow depicted in *Figure 10.*
The G&H separation nut has been qualified at supplier level on the basis of existing nut qualification data and flight heritage with the only exception of a delta qualification for the sine environment.
The remaining key component of the mechanism was therefore the separation interface. Since design concept, materials and coatings of such interfaces are exactly the same for floatation and parachute panel it has been decided to perform the qualification campaign on the most stressed mechanism only, i.e. the parachute mechanism which uses smaller components.
Being the risk of floatation mechanism spring failure remote it has been decided in agreement with the customer to perform the qualification of the entire floatation mechanism assembly only during system test campaign.
After qualification at mechanism level the floatation mechanisms have been functionally tested at customer premises by means of panel ejection test on ground and during IXV drop test.

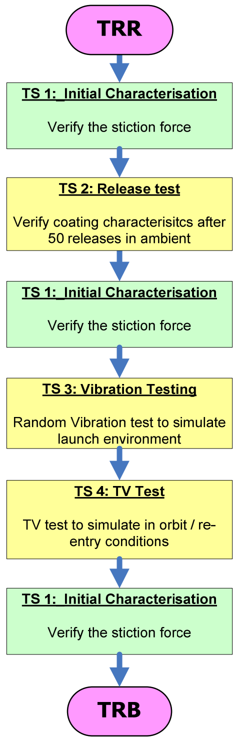

Figure 10. Qualification test flow(mechanism level)

The successful accomplishment of the test campaign performed by RUAG together with the positive results of customer testing activities have release the jettison mechanism design for the flight.

3. MECHANISM TEST AT SUBSYSTEM LEVEL

Beside standard test campaign including vibration and thermal vacuum test, dedicated test has been performed aiming at understanding the overall capability of the mechanism design to allow panel bracket rotation with low friction. The test has been executed on a complete spherical joint assembly including not only the contact rings of separation interface but also the spherical washers and panel bracket. The setup for the test on floatation mechanism is shown in *Figure 11*.

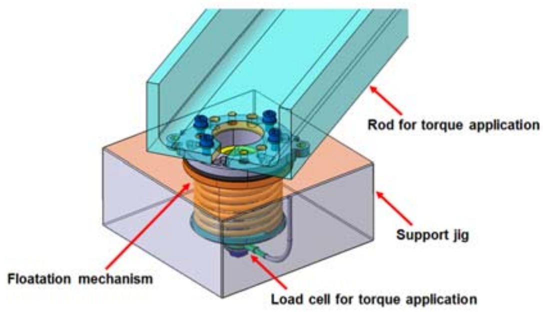

Figure 11. Rotation test setup

The parts, mounted on a jig to house the contact ring fitted on the cold structure were assembled with the design preload, monitored by a load cell in series with the nut replacing the G&H. By using a bar fitted at one

side to the panel bracket a torque was applied to the mechanism via a controlled force on the other side which was measured by a spring gauge until the panel interface starts rotating. The test was repeated on the parachute mechanism as well. To improve the confidence about effect of manufacturing tolerances of contact ring and spherical washers some shims were added underneath the spherical washers to induce misalignment of the centre of rotation of separation interface rings with respect to centre of rotation of the spherical washers assembly. The results of this test are reported in *Figure 12* for different starting angle.
With the only exception of the extreme case of 0.4mm shim no significant effect has been measured.

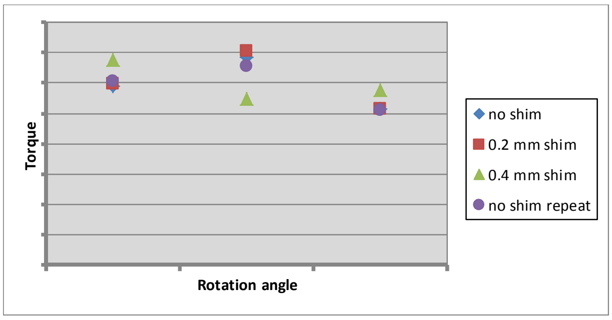

Figure 12. Rotation test results

Similar results have been found for the parachute mechanism.
As reported above both vibration and thermal vacuum tests have been performed on the most critical mechanism in terms of separation ring stresses which is the parachute mechanism.
The vibration test has been performed with the configuration presented in *Figure 13*. A dummy mass has been used to generate the axial and lateral loading on the separation interface. By inclining the separation interface it has been made possible to apply loads in both in plane and out of plane directions at the same time which represented a more critical load condition than standard load application in one direction only.

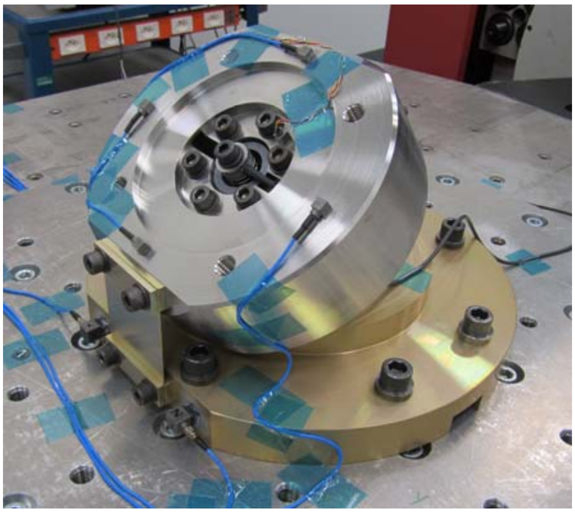

Figure 13. Vibration test setup

Vibration excitation along three in plane directions at 0°, 60° and 120° has been applied to better check that contact ring performance were homogeneous and not affected by manufacturing tolerances.
Moreover the load cell in series with the separation bolt has been kept to monitor separation bolt preload variation. Despite the dummy mass has been designed to have centre of gravity coincident with the centre of rotation of the mechanism, two additional blades has been installed.
The defined random vibration spectrum was such that, with the implemented dummy mass, the shear and axial loads RMS (3σ values) acting on separation interface were the same as the quasi-static loads specified for mechanism design. This approach has been used since it has been considered that in terms of fretting or cold welding of separation interface vibration loads are more critical than loads statically applied and, on the other hand, the parts were designed to be able to withstand such load condition.
Thermal vacuum test has been performed as well. The setup for the test is depicted in *Figure 14*.
Moreover the separation interface was open and closed 40 times to simulate, including the required safety factors, the mating and de-mating which could occur during on-ground activities.

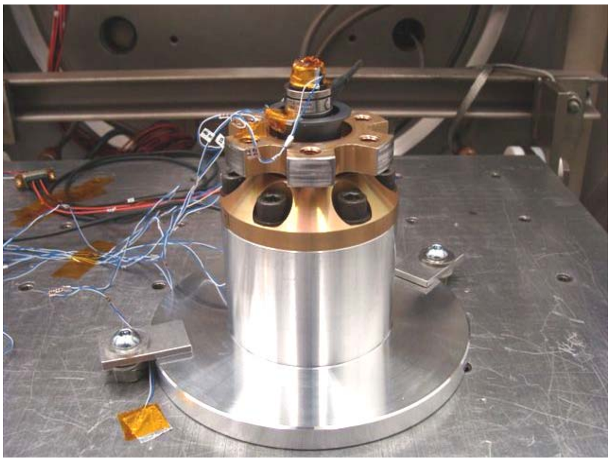

Figure 14. Thermal vacuum test setup

At the end of thermal vacuum it was verified that vibration and thermal stresses combined with repeated mating and de-mating did not produce damage of the separation interface components. The force needed for contact rings separation has been checked by means of a spring gauge, The test was successful since the force measured force was below the spring gauge accuracy equal to 2N.
Besides environmental test, due to the high importance of separation bolt preload and being a direct measure of such preload on the flight hardware not possible, characterisation of separation bolt preload with respect to mounting torque for all the delivered separation nuts has been performed. Test has been run by using a set-up which included a load washer in series with the flight separation bolt and the spherical washers assembly.

4. MECHANISM TEST AT SYSTEM LEVEL

At system level two tests have been performed on floatation mechanism.

Floatation panel assemblies and mechanisms identical to flight units have been integrated in IXV vehicle mock-up ant then on ground tested to verify the capability of mechanism to properly release the panel.

During the ground test the panel trajectory has been measured by high speed camera system and panel trajectory rebuilt.

In *Figure 15* some frames of the video concerning release of the front left panel are shown.

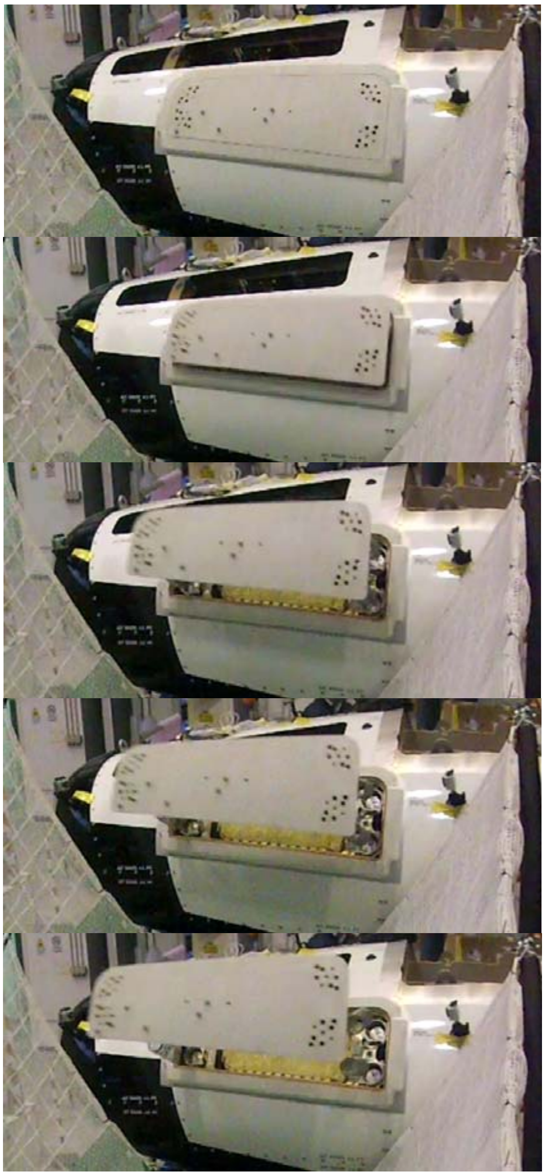

Figure 15. Front panel release test (Courtesy of Thales Alenia Space Italy)

In *Figure 16* and *Figure 17* the measured panel centre of gravity displacements and rotations are presented.

In the graphs below X, Y and Z directions are respectively the IXV longitudinal, lateral and vertical axis.

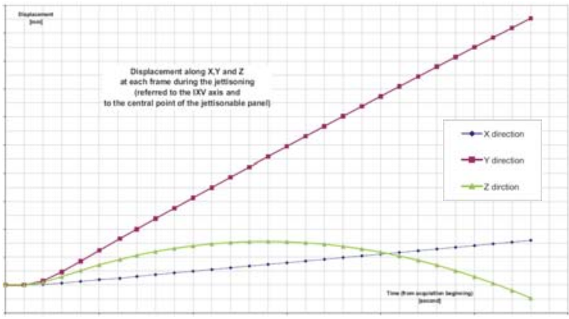

Figure 16. Front panel trajectory – displacement (Courtesy of Thales Alenia Space Italy)

From the plot it can be noticed that the panel separation from the vehicle occurs without significant panel pitch and yaw confirming the capability of the four mechanisms to perform the release with a time scatter in the order of few milliseconds, when subjected to a synchronous activation signal, and to provide a balanced ejection force at the four panel corners.

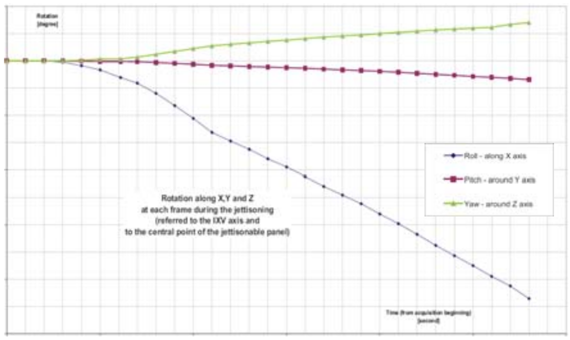

Figure 17. Front panel trajectory – rotations (Courtesy of Thales Alenia Space Italy)

The same test has been performed on the rear floatation panel and also in this case the release performance matched the expectations.

The floatation panels after mechanism refurbishment were further tested during the IXV drop test. This test was aimed at the validation of the water landing system including the subsonic parachute, flotation balloons, and beacon deployment.

The test was performed on the mock-up shown in *Figure 18*.

Figure 18. IXV mock-up for drop test (Courtesy of Thales Alenia Space Italy)

In the initial phase, after separation from the helicopter which brought the mock-up at an altitude of approximately 3000 m, the floatation panel were successfully ejected to allow deployment of the floatation balloons.

Figure 19. IXV mock-up recovered after splash down (Courtesy of Thales Alenia Space Italy)

Following the successful test campaign at subsystem and system level described above the manufacturing of floatation and parachute mechanism flight models has been released.
The flight components installed on the cold structure are show in the *Figure 20* and *Figure 21*. In *Figure 20* the safety pins preventing unwanted activation of the mechanism can be also seen.

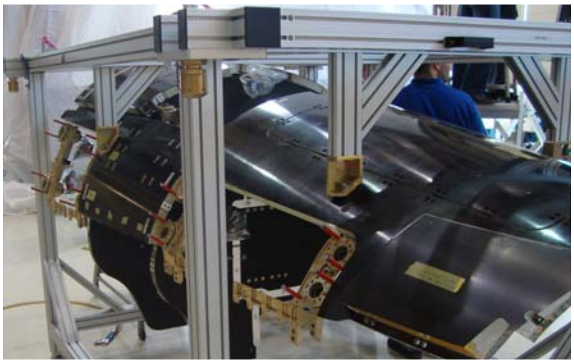

Figure 20. Left floatation mechanisms

Figure 21. Parachute mechanism detail

Flight mechanisms, integrated in the IXV cold structure, have been then environmentally tested and declared ready for flight.

5. CONCLUSIONS

Functional and environmental test at system level and afterwards the successful IXV flight proved that the jettison mechanism design concept were able to match the mission needs.
Moreover it can be assessed that the test campaign defined at mechanism level focused on checking the key components only, in particular the separation interface and the separation nut, allowed to verify the capability of the jettison mechanism of fulfilling the requirements.

Figure 22. IXV during Vega fairing encapsulation (photo: ESA)

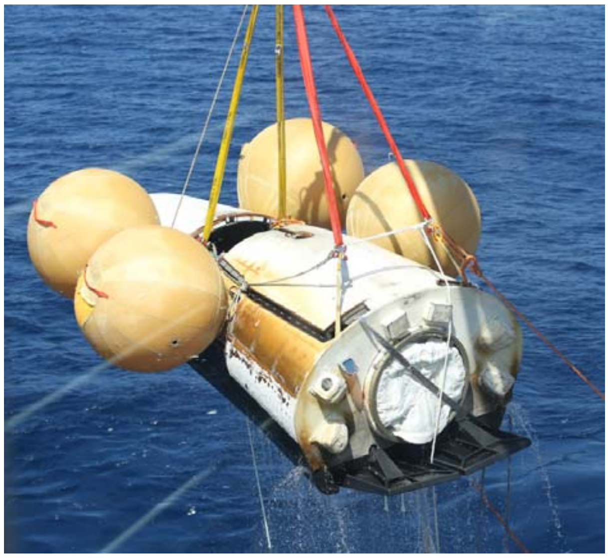

Figure 23. IXV recovery (photo: ESA)

6. Acknowledgments

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