SEARCH AND RESCUE – DEVELOPMENT AND VERIFICATION OF A MODERNIZED PASSIVE FLOATING SYSTEM FOR PAYLOAD SEA RECOVERY

Johannes Göser[(1)], Oliver Drescher[(2)], Marcus Hörschgen-Eggers[(3)], Ulf Gemeinhardt[(4)]

[(1)] *Deutsches Zentrum für Luft- und Raumfahrt (DLR)/Oberpfaffenhofen, Mobile Raketen Basis, Münchener Straße 20 82234 Weßling, Germany, E-mail: johannes.goeser@dlr.de*

[(2)] *Deutsches Zentrum für Luft- und Raumfahrt (DLR)/Oberpfaffenhofen, Mobile Raketen Basis, Münchener Straße 20 82234 Weßling, Germany, E-mail: oliver.drescher@dlr.de*

[(3)] *Deutsches Zentrum für Luft- und Raumfahrt (DLR)/Oberpfaffenhofen, Mobile Raketen Basis, Münchener Straße 20 82234 Weßling, Germany, E-mail: marcus.hoerschgen-eggers@dlr.de*

[(4)] *TEXCON GmbH, Bruchweg 22-24, 37632 Eschershausen, Germany, E-mail: ulf@texcon.de*

ABSTRACT

For most suborbital space flights, the successful recovery of the experimental payload is a critical point at the very end of the mission. Beside land based recovery, particular missions require a sea recovery in the Arctic Ocean. Therefore, a variety of passive floating systems have been developed and used by DLR's Mobile Rocket Base (MORABA).

Using the vast experience of multiple successful sea recoveries over the last decades, some of the latest development work has been dedicated to a modernised version. In cooperation with TEXCON GmbH, improved long-term floating behaviour and a considerably reduced packing volume have been achieved by using innovative materials and manufacturing technologies.

Prior to the first successful operation of the improved passive floating system, various tests had to be performed to verify the floater's functionality and durability. In this context, the Neutral Buoyancy Facility's (NBF) diving pool of ESA's European Astronaut Centre (EAC) in Cologne was offered for investigating different recovery scenarios.

This paper describes the development and verification process of the modernized passive floating system. Furthermore, results of the first successful operation during the PMWE mission are presented.

1. INTRODUCTION

For the safe retrieval of experiments on sounding rockets, MORABA uses various recovery systems customized for the challenges of the particular missions. Besides different payload masses, experiment configurations and re-entry velocities, the impact area is a decisive design factor. Recovery systems that are developed and used by MORABA consist of a two staged parachute system with a first stage stabilization parachute and a second stage main parachute. During the payload descent the parachute system is activated by barometric pressure switches and decelerates the payload to comfortable impact velocities below 15 m/s. At several launch sites all around the world sounding rockets are launched towards the sea. This offers a wide range of possible impact areas without affecting or disturbing populated areas. To enable a payload recovery at sea, MORABA uses floating systems that are mounted to the main parachute's apex and are passively inflated by the ram air during descent. The floater is finally sealed by a duckbill valve and prevents the payload from sinking after touchdown.

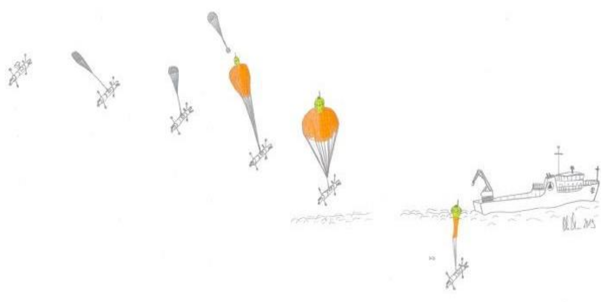

Figure 1 Sketch of typical sea recovery sequence

Because of its two chamber design, the floater still generates buoyancy even if there is a rupture on the outer shell. The size of the floater body can vary, depending on the mass of the payload. For localisation a GPS/Iridium transceiver, a VHF radio beacon transmitter and a strobe light for visual detection are installed in a watertight box that is mounted on the floater's apex. After visual detection the floater can be hooked at a salvage line and hoisted off the water together with the parachute and the payload. Those kind of floating recovery systems have been used for multiple missions during the last 50 years.

Figure 2 Previous passive floating system

Most of the recovery operations have been successful whereas several findings and weaknesses could be revealed. For example, the poor tightness of the floater material and the joints increased the probability of a mission failure because of payload sinking. The gained experience combined with modern manufacturing methods showed the potential for the development of an improved and more reliable passive floating system for payload sea recovery.

2. DEVELOPMENT

The development of the modernized version of the passive floating system has been performed in cooperation with the manufacturer TEXCON GmbH. Initially, MORABA worked out a technical specification document to determine the requirements of the new system [1]. The general functionality of the modernized floater system shall not be changed compared to the previous floater system. Improvements of the material and the manufacturing method shall be the main focus of the modernization. MORABA engineers expect an improved tightness of the floater material and joints redesign. A long time buoyancy of 48 hours is required. Furthermore, the visibility of the floater system shall be improved by using signal colour with reflector markings.

Similar to the most commonly used system in the past the new floater shall have a capacity of 320l and thereby generate sufficient buoyancy to keep a 200kg payload in surface waters. It shall have a maximum packing volume of $4dm^3$ and a maximum mass of 1.5kg [1].

The previously used floating system was made of Rivertex 240 material (mass: $240g/m^2$, hydrostatic head: >3000mm) and manufactured by adhesive bonding [2]. Both the material and the joints started leaking over time. The company TEXCON GmbH proposed to use 804 FL Yellow material (mass: $153g/m^2$, hydrostatic head: 155100mm) for the floater body [3]. It is a polyurethane coated polyamide fabric that is commonly used by TEXCON GmbH to design life vests. Besides the lower mass and the higher hydrostatic head the distinctive and bright colour of the material meets the requirement of a better visibility. Different to the previous design the single strips are not bonded but connected by ultrasonic welding and high frequency welding. This technique provides more reliable, homogenous and tight joints. A first prototype of the redesigned floater was manufactured and completed after one day. In comparison the production of the previous floater took multiple days. The final mass of the floater body prototype is 0.89kg, which results in a mass reduction of 40% compared to the previous design (1.53kg).

Figure 3 New (left) and previous (right) floater design

For the qualification of the new material and the new manufacturing method tensile tests of the material and the joints were performed. Furthermore, burst tests were conducted for several prototypes. The test results are compared to the expected flight loads in order to determine safety factors of the system.

2.1. Determination of Flight Loads

The floater is inflated by the ram air in the main parachute canopy. It is deployed together with the main parachute at an altitude of approximately 3300m and a velocity between 35-50m/s. The dynamic pressure in the canopy is calculated with Eq. 2-1

$$p_{dyn} = \frac{1}{2}\rho v^2 \qquad \text{2-1}$$

where ρ is the density and v the velocity of the body. The density is dependent on the air pressure and temperature. It is determined with Eq.2-2.

$$\rho = \frac{p_0}{R_S T_0} \qquad \text{2-2}$$

R_s is the specific gas constant, p_0 the air pressure and T_0 the air temperature. The specific gas constant is defined with R_s=287.05J/kgK. Values for the altitude dependent air pressure and temperature are gained by using the simplified Boltzmann barometric equation (Eq. 2-3) for the air pressure and a constant air temperature of T_0=273.15K.

$$p_o = \mathrm{p}\, e^{(-\frac{H}{H_0})} \qquad 2\text{-}3$$

H_0 is defined with 7990m and p is the pressure of the standard atmosphere 101325Pa. An opening velocity of 50m/s results in a theoretical dynamic pressure of 10.7mbar in the parachute canopy and in the floater. As the dynamic pressure is highly dependent on the velocity it rapidly decreases after the deceleration of the main parachute. The floater is inflated during the first seconds after deployment. When the final sink rate velocity of 14m/s is reached the dynamic pressure in the canopy decreases to 1-2mbar. Taking into account that a negative pressure area is created around the outer shell of the canopy during deployment and the first opening shock could be even higher than the theoretically calculated 10.7mbar, a floater filling pressure of 30mbar was defined for further calculations and testing activities.
For the simplified calculation of the tensile stress in the floater material the boiler formula for spherical bodies is used (Eq. 2-4).

$$\sigma = \frac{pr}{2t} \qquad 2\text{-}4$$

Here, p is the positive pressure in the floater, r the radius of the floater body and t the thickness of the material. A positive pressure of 30mbar, a floater radius of 425mm and a material thickness of 1mm results in a tensile stress of 0,63N/mm^2. Tensile tests shall prove that the new floater material and joints withstand higher stresses.

2.2. Tensile Test

The data sheet of the 804 FL Yellow fabric specifies a tensile strength of 438N/25mm in warp direction and 350N/25mm in weft direction [3]. The qualification process at TEXCON GmbH included the validation of these values by testing three samples with a width of 50mm in each direction. Average tear strengths of 800N were measured, whereas the values in weft direction were slightly lower than the ones in warp direction [4].

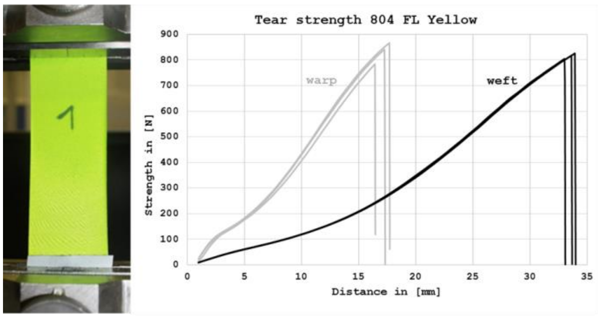

Figure 4 Tear strength 804 FL Yellow

This difference is documented in the data sheet, too. Considering that twice as wide samples were used the measurement of twice as high tear strengths can be explained. For the calculation of the tensile stress in Eq. 2-5, the defined material thickness of 1mm is used again.

$$\sigma = \frac{F}{A} = \frac{800N}{50mm * 1mm} = 16\,\frac{N}{mm^2} \qquad 2\text{-}5$$

The result corresponds to a safety factor of 25 compared to the determined tensile stress during flight.
For the determination of the joints' tear strength, five test samples of each welding configuration on the floater were manufactured [4]. Three different welding configurations exist on the floater. They are presented in Table 1.

Table 1 Different tensile test configurations

(a)		5mm ultrasonic welded joint 
(b)		6mm high frequency welded joint 
(c)		6mm high frequency welded joint & 5mm ultrasonic welded joint (90°) 

Besides the tear strength, the tests shall reveal the failure pattern of the welded joints. In Table 2 the results of the tensile tests are presented. The crack pattern is described and the average and minimum tear strength of each configuration is listed.

Table 2 Results of the joints' tensile tests

	Crack Pattern	F_{av} [N] / F_{min} [N]
(a)	Along edge of welded joint	420 / 350
(b)	Along edge of welded joint	450 / 450
(c)	Along edge of high frequency welded joint	350 / 200

For all tests the welded joints never failed. The transition from the joint to the material is the weak point of the construction. Test configuration (c) failed at average forces of 350N whereby the minimum reached tear strength was 200N [4].
To get conservative results the maximum qualified tensile stress for the joints is calculated with the minimum reached tear strength of the test series.

$$\sigma = \frac{F}{A} = \frac{200N}{50mm * 1mm} = 4\,\frac{N}{mm^2} \qquad 2\text{-}3$$

In comparison to the pre-determined tensile stress during flight the joint tensile tests result in a safety factor of at least 6.3.

2.3. Burst Test

The investigation of the new material and manufacturing method was further supported by burst tests on five prototypes [4]. During the test series several weak points, as the sewed joints between the duckbill valve and the inner membrane that part the floater volume, were fixed and reinforced. This joint is essential for the correct function of the duckbill valve. In case of a failure, the duckbill valve is pushed outwards and the floater starts leaking.
For the burst tests the floater was inflated via a pressure port at the apex of the floater body. Additionally, the inner pressure was measured via a second port at the apex.

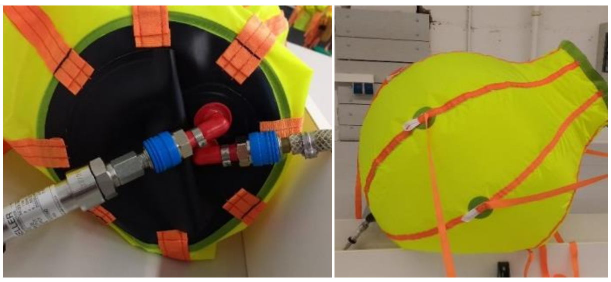

Figure 5 Burst test assembly

The result of the burst test of prototype 4 is exemplarily showed in Figure 6. At this test the joint between the duckbill valve and the membrane was sufficiently reinforced with heat welded tape.

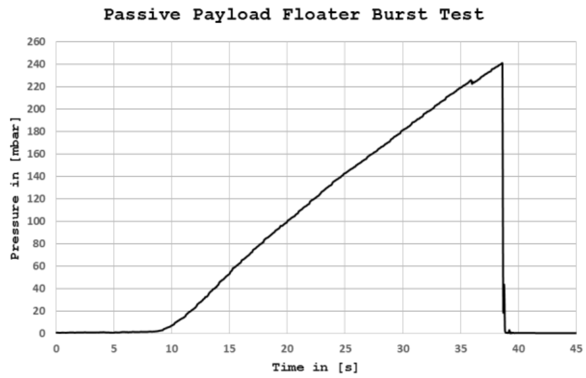

Figure 6 Result of burst test 4

The floater failed at a burst pressure of 240mbar [4]. For the comparison of the tensile stresses the boiler formula (Eq. 2-4) is used again. For the burst pressure of 240mbar the tensile stress leads to 4,89N/mm^2, which is close to the minimum reached tear strength of the joints' tensile tests. A safety factor of 8 compared to the determined flight loads is reached. The results of the burst tests correspond to the results of the tensile test and verify the design as well as the test results.

3. QUALIFICATION TESTING

In addition to successful dimensioning of the modernized passive payload floater, the functionality in use has to be proven. The offered diving pool of ESA's NBF provides a controlled environment to perform different recovery scenarios.

Figure 7 Neutral Buoyancy Facility

The successful qualification of the modernized floater includes buoyancy tests with different masses, a long duration buoyancy test, a recovery hoisting test and the investigation of the failure behaviour. In addition a drop test was planned to get information about the loading during touchdown. For comparison the buoyancy tests were performed for the previous floater, too.

3.1. Buoyancy Tests

To enable buoyancy tests with different payload masses a load harness was designed and sewed to the lower flange of the test floater. The load harness was mounted to a dummy mass carrier (net mass 21kg) that can be equipped with a variable amount of rubber insulated weight plates á 25kg. Furthermore a GoPro camera was mounted to the harness to record the behaviour of the duckbill valve during operation. To keep the floater unloaded while lifting it into the water a load beam construction was developed. It is shown in Figure 8.

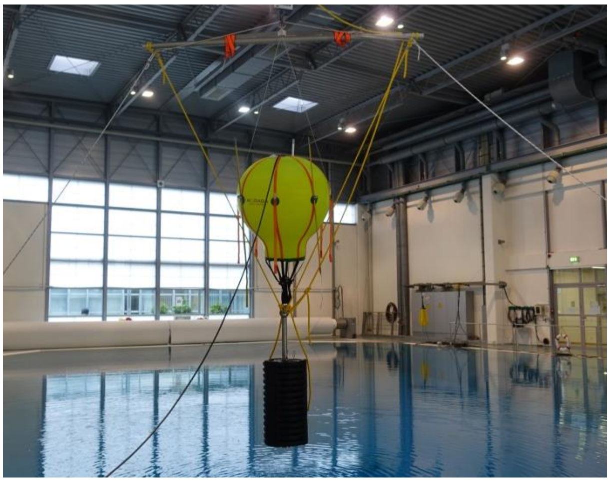

Figure 8 Load beam construction

When the floater is set down on the water surface the suspension ropes of the load beam are released and the dummy payload mass is finally carried by the floater. Buoyancy tests were performed with three different payload masses (100kg, 200kg and 350kg). For all tests the floaters were inflated with the same initial pressure of 30mbar. The test duration for each test level was 60min. All tests were performed for the new and the old floater. During the buoyancy tests the differential pressure and the temperature was measured. Furthermore draft marks were placed around the payload floater to observe the sinking level of the floater over time.

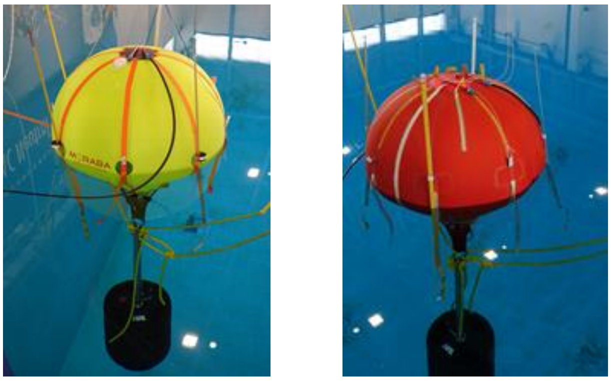

Figure 9 Buoyancy tests with new (left) and previous (right) floater

The buoyancy test confirmed the improved performance of the modernized payload floater. For all mass levels the previous floater system started leaking over time and was filled with water after each test. Bubbles rose along the floater, indicating that the duckbill valve is not perfectly watertight. The video of the GoPro camera confirmed that the duckbill valve was partly open. Furthermore the floater fabric was completely soaked, which supports the suggestion that it is water permeable after a certain time. The draft marks identified that the floater sunk for at least 50mm during each test. In comparison the modernised floater passed all mass levels without leaking or significant sinking. The draft marks showed similar levels at the beginning and the end of the test. A pressure drop of 1-3mbar within 60min was measured. The pressure measurements on the previous floater system are not conclusive and comparable as the huge amount of infiltrating water further compressed the residual air and influenced the measurement.
To investigate the limits of the system a buoyancy test with 350kg payload mass was performed for each floater. Before the qualification tests the dimensions of the test prototypes were checked. It turned out that the floater volume of the new floater was slightly bigger than specified due to manufacturing inaccuracies and fabric stretching (~360l). Furthermore, the defined 320l refer to a spherical volume. In reality the volume is bigger due to the additional volume at the duckbill valve. The 350kg test had to be aborted for the previous floater because it failed at the lower flange after 30min. In contrast the new floater system passed this test level with no water entering the floater.
At the long duration buoyancy test the endurance of the modernised floater system was further investigated. The test was performed with a 200kg payload mass for 14,5h. The pressure plot is shown in Figure 10.

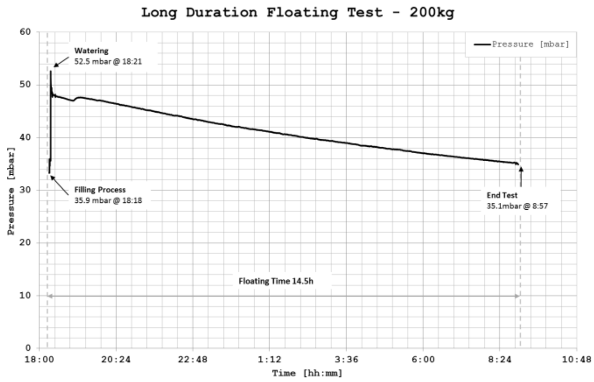

Figure 10 Pressure measurement long duration buoyancy test

Similar to the previous buoyancy tests the floater was inflated to a pressure of approximately 30mbar. When the floater was set down on the water surface the pressure increased to 51mbar as the floater was compressed by the surrounding water. After 14.5h the pressure level decreased to 35mbar. The draft marks showed that the floater sunk about 30mm and just some water puddles accumulated in the floater. A closer look to Figure 10 reveals that the course of the plot is not proportional over time but the gradient of the pressure loss decreases. A trend line analysis displayed that after 48h the pressure inside the floater still would have been 17mbar. The buoyancy performance of the modernized passive payload floater has been satisfying. The improvement compared to the previous floater system was clearly proven.

3.2. Recovery Test and Test of Failure Behaviour

The recovery test showed whether the modernized floater can withstand the loads that occur when it is hoisted off the water together with the payload. To lift the floater a salvage line is installed, which is passed through 8 sewed-on loops around the circumference. The salvage line is used to grab the floater with a crane hook. For the recovery test the floater was loaded with a dummy payload mass of 200kg.

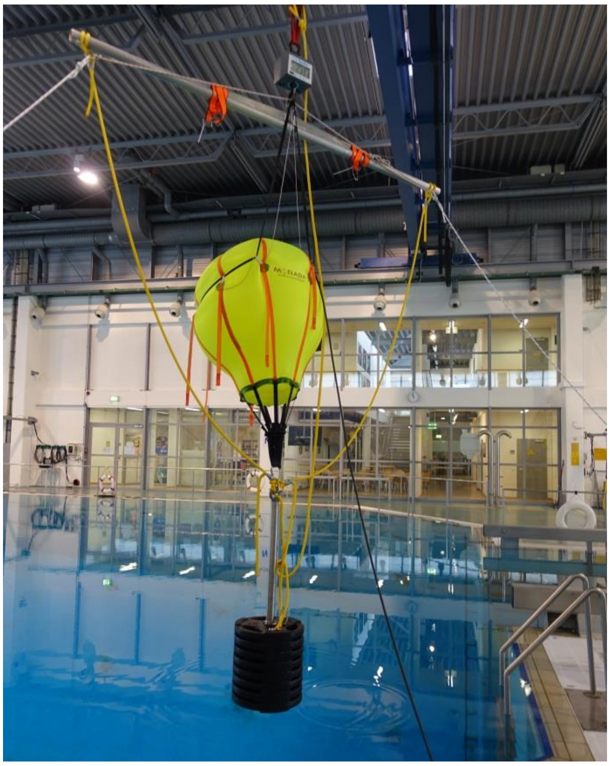

Figure 11 Recovery test at NBF

The floater and the dummy payload mass were successfully hoisted. No damage was observed on the floater structure.
Besides the recovery operation the failure behaviour of the floater was further investigated. The two chamber design of the floater should still generate buoyancy even if there is a rupture in the floater body. To simulate this scenario without damaging the floater body a valve was integrated to the floater body, which could be manually opened when assembly is floating. This test was performed with a payload mass of 100kg. Adding the mass of the dummy mass carrier the resulting actual payload mass was 121kg. After the valve was opened the payload floater deflated, however the membrane avoided that that all air was released. Because of the pressure drop in one compartment, the fabric around the duckbill valve lost its tension and failed. Water got inside the floater body and avoided that the air in the second compartment could leak out, too. The floater still generated enough buoyancy to carry the payload. The half-filled floater is shown in Figure 12.

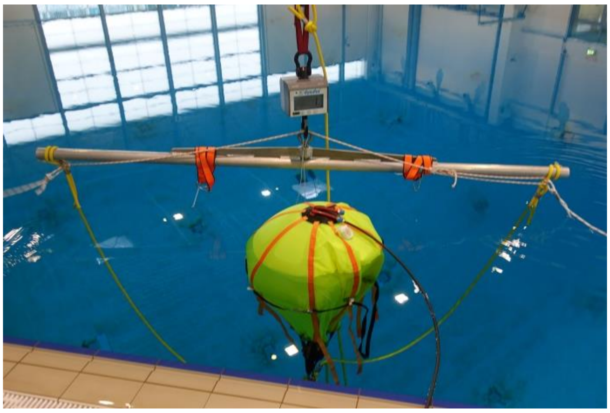

Figure 12 Failure behaviour test

To investigate the floating behaviour in this configuration, a 60min buoyancy test was performed. No changes could be detected during the test. At the end of the test the “damaged” floater still generated sufficient buoyancy for the payload. The test confirmed that the membrane technique is working.

3.3. Drop Test

A decisive event during the parachute sequence is the splashdown of the payload and the floater. As the waiting position of the recovery vessel is multiple kilometres away from the expected impact point the splashdown was never observed from the vessel nor recorded by on-board telemetry. The final sink velocity of previous missions is 10-15m/s. Although it is expected that only the payload hits the water with this velocity and the parachute and floater impact velocity is much lower, a floater drop test with a payload mass of 175kg was conducted.
For the test the dummy mass and the floater were lifted up to an altitude of 3m above the water surface corresponding to an impact velocity of around ~8m/s. Despite the rather unrealistic test conditions the result was of general interest, as an active recovery system with inflatable balloons on the payload is also considered as a future development project. The test shows the robustness of the material in case of a hard impact (see Figure 13). The assembly was released by a snap shackle.

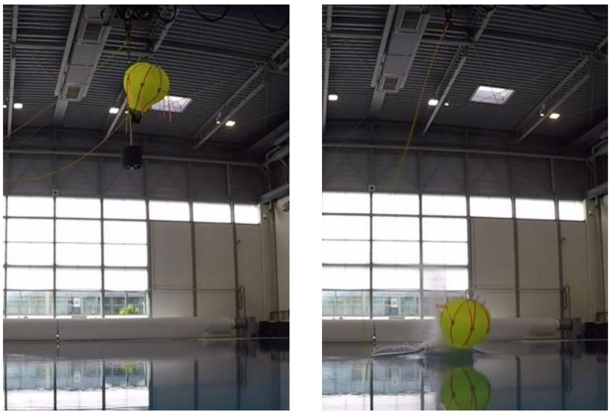

Figure 13 Drop test at ESA NBF

During the splashdown the floater body failed. Because of its small surface area the dummy mass did not decelerate the complete assembly very much. Because of that the floater hit the water surface with almost the same velocity. Cracks around the lower flange and along one of the strip joints were detected. The test revealed that the development of an active recovery system would require further investigations concerning the robustness of the inflated balloons. For the qualification of the passive floater system the successful conduction of this drop test was not essential. To further support the assumption that the parachute and floater hit the surface with much lower speed, a touchdown analysis of available on board video material was performed [5]. It showed that the suspension lines are relaxed after payload touchdown and the parachute slowly sinks to the ground.

Figure 14 Parachute sinking to the ground

A video analysis showed that the parachute usually hits the ground or water surface with velocities between 1-3m/s [5].

4. FLIGHT OPERATION

In April 2018 the PMWE 1 and 2 mission was conducted at Andøya Space Center in Norway. During the campaign two single stage rockets were successfully launched and the instrumented payloads recovered. The mission goal aimed at the investigation of polar mesospheric winter echos (PMWE), which occur at altitudes from 60 to 90km.
Both rockets were boosted by an Improved Malemute motor and were equipped with the modernized passive floating recovery system. The payload masses in recovery configuration were 161.3kg (PMWE 1) and 159.3kg (PMWE 2) [6].

Figure 15 PMWE 2 vehicle at the launcher

For the recovery operation the service and off-shore work boat MS Niklas from FDA (Finnsnes Dykk & Anleggservice AS) was hired, which is equipped with two 20m cranes that facilitate payload recovery from 10m below the sea surface [7]. Prior to the campaign a VHF direction finder has been installed on board to receive the signal of the radio beacon transmitter. Three crew members of MS Niklas and one member of MORABA finally performed the recovery operation on deck.

Figure 16 Recovery vessel MS Niklas

4.1. Recovery Operation

The rockets were launched on April 13th and April 18th 2018. On both launch days the weather and sea conditions were good, with sea state levels between 2Bft (PMWE 1) and 3Bft (PMWE 2) [8]. To minimize the time of the floater and payload in the water, the recovery vessel went to a safe waiting position, three hours away from the harbour, before the launch window opened.

Both payloads were located within two hours after splashdown. About one hour before visual detection, the beacon signal, transmitted by the floater, was received. The bright yellow colour of the modernised floater created a good contrast to the sea water and therefore the floater was easily localized. Pictures of the PMWE 1 and PMWE 2 floating systems before recovery are shown in Figure 17. The observed draft of the floaters is different. For the PMWE 1 floater 80% of the body volume was above water surface whereas only 60% of the body volume was above water surface for the PMWE 2 floater.

Figure 17 PMWE 1 and PMWE 2 floating in the sea

After the recovery vessel got close enough to the floater one of the crane hooks was manually clipped to the salvage line. As the payload is hanging 10m below water surface and the draft of MS Niklas is 4.35m, the payload could not hit the hull of the recovery vessel [7]. Exemplary for both payloads the recovery operation of the PMWE 1 payload is illustrated in Figure 18.

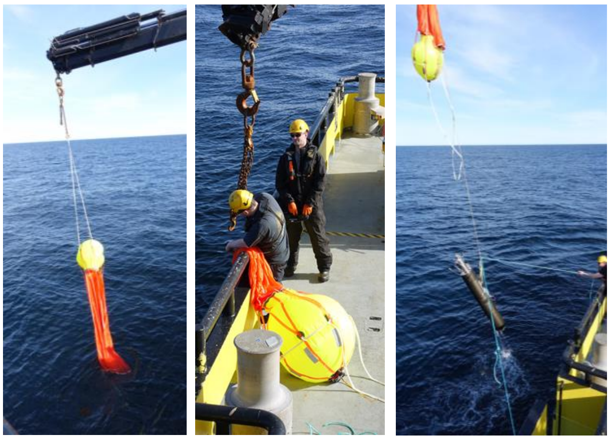

Figure 18 Recovery operation of PMWE 1

The hoisting of the payload was performed in two steps. Although the cranes of this vessel may be big enough to hoist the payload in one step, it is a safer manoeuvre to perform the recovery in two steps.

First, the floater was lifted about 1m over the ship rail, ensuring that the payload was still below the vessel's hull. After that the floater was taken on board and the parachute was knotted with a sling to the ship rail. Subsequent to that the crane hook was released from the salvage line and hooked to the created sling. Finally the sling was released from the rail and the payload was completely hoisted and pulled on board.

One advantage of a two-step hoisting is that the floater is only stressed when the payload is still in the water. For both recoveries the floater was not damaged by the stress of the salvage line, constricting the floater body.

After each recovery the floater was further inspected. Concerning the tightness a significant difference was detected. Whereas 1-2l of water were inside the PMWE 1 floater considerably more water was caught inside the PMWE 2 floater. Over 30l must have been inside this floater. A picture of the water inside the PMWE 2 floater is shown in Figure 19.

Figure 19 Water inside the PMWE 2 floater

The different amount of water inside the floater explains the different draft of the floaters that was observed before the recoveries (see Figure 17). Considering the short floating time and the moderate sea state level, the amount of water inside the PMWE 2 floater is not satisfactory. During the qualification tests at the ESA NBF such a huge amount of water was never observed inside the modernized floater. Two major differences to the ESA NBF tests are the sea state conditions that could not be simulated in the NBF pool and the stabilization straps connecting the floater to the main parachute. During flotation the main load of the payload is transferred via those straps and not via the floater's base, which is why the less centred floater body could start shaking by the waves. This process is displayed in Figure 20.

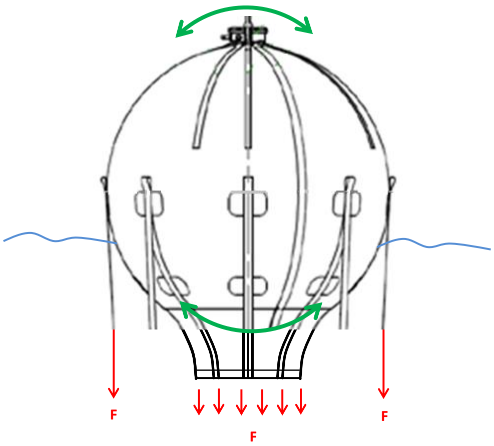

Figure 20 Schematic of floater shaking

This shaking can support water entering the floater via the duckbill valve. A post flight leakage test of both floaters proved that the floater bodies are still completely tight, which confirms that the water must have entered into the floater via the duckbill valve. On basis of these findings a further qualification test series at a wave channel facility is planned to further investigate and understand the impact of waves on the tightness of the duckbill valve.

5. CONCLUSION

A modernized version of MORABA's passive payload floater was designed, tested and flight qualified. In cooperation with TEXCON GmbH a new material and manufacturing method was selected, expecting an improved buoyancy performance for the floater. During the test phase at ESA's NBF, the new floater was subjected to key scenarios of the recovery operation. The buoyancy tests showed the advantages of the modernized floater compared to the previous floater. For the PMWE 1 and 2 campaign the modernised floater system was used first time in flight. Both payloads were successfully recovered. However, the recovery performance also revealed that the system, especially the valve, is sensible to the sea state conditions. To further understand and improve the behaviour of the duckbill valve, a test in a wave channel facility is planned. Furthermore the installation of a 360° camera at the floater apex is considered, which provides footage on the floater behaviour during touchdown.

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