WPA Mk I: On orbit and on ground investigations and refurbishment activities

G. Bufano[1], G. Truscelli[2], A. Itta[3], R. Bianchi[4],
Thales Alenia Space, Turin, Italy

Jan Persson[5], Stephan Hinderer[6]
European Space Agency, Noordwijk, The Netherlands

This paper describes the flux of on orbit and on ground investigations that have involved the Water Pump Assembly (WPA) Mk I, from the issue detection to the identification of the subsystem involved, until the detailed investigation of the causes and the WPA refurbishment and re-acceptance.

The WPA Mk I was replaced with the spare unit in July 2013, then downloaded and successfully refurbished.

The on orbit investigation demonstrated that the hydraulic section had worked properly and that the issue had occurred on the electric section. The ground investigation was composed of two stages, which could not be performed on orbit since the WPA Mk I was a unique Orbit Replaceable Unit (ORU), differently from the Mk II that is composed of different ORUs. The first stage was a series of tests, programmed in such a way to identify whether it had occurred in the motor or in the electronic box: the result was to locate the failure in the electric box. The second stage was a set of dedicated electrical tests to track down the location of the issue: the result was to identify the failed board. This complex activity required to accurately plan the sequence and the type of tests in order to be able to unambiguously identify the problem.

Since no spare WPA units are available for the time being, a re-acceptance campaign of the downloaded and repaired unit is necessary. The re-acceptance campaign has been completed and the re-accepted unit is ready for uploading, if necessary.

In the meantime the WPA Mk II is undergoing the qualification campaign and when ready it will be launched to replace the current unit as necessary. The issue that has been detected on the Mk I is not expected on the Mk II, because the latter electronic box design is based on a different, more innovative technology.

Nomenclature

ATCS	=	Active Thermal Cooling System
DMS	=	Data Management System
ESA	=	European Space Agency
EPC	=	Electronic Power Converter
FEM	=	Finite Element Model
FM	=	Flight Model
GND	=	?
HTV	=	H-II Transfer Vehicle
MRB	=	Material Review Board
ORU	=	Orbit Replaceable Unit
QD	=	Quick Disconnect
PCB	=	Printed Circuit Board
PDI	=	Pre-integrated Development Item
PDU	=	Power Distribution Unit
PWM	=	?
WPA	=	Water Pump Assembly
WSK	=	Water Service Kit
WPU	=	Water Pump Unit

[1] Thermal Engineer, gaetana.bufano@thalesaleniaspace.com
[2] Thermal Engineer, gianni.truscelli@external.thalesaleniaspace.com
[3] Structural Engineer, antonietta.itta@thalesaleniaspace.com
[4] Electrical Engineer, renato.bianchi@thalesaleniaspace.com
[5] Thermal Engineer, jan.persson@esa.int
[6] Systems Engineer, stephan.hinderer@esa.int,stephan.hinderer@strategyand.nl.pwc.com

I.

II. Introduction

The Active Thermal Cooling System (ATCS) is the system aimed to provide water cooling to all Columbus equipment and Payloads. The core of this system is the Water Pump Assembly (WPA), which provides loop pressurization, water circulation, compensation and filtering and, by means of a dedicated Electronic Package Controller (and related embedded software) manages all the ATCS automatic controls.

Two identical WPA (1 & 2) are mounted in Columbus in cold redundancy configuration.

On January 13th, 2013 a planned switch-over (S/O) from WPA1 and WPA2 aborted: WPA2 did not start running and the system was automatically reconfigured back with WPA1 running again. Telemetry investigation started immediately and on January 21st, a dedicated test on-orbit excluded a hydraulic or mechanical damage and restricted the failure options to either the pump impeller or the related electronic; the WPA2 was declared failed. ATCS was running nominally on WPA1 but the redundancy was lost. It was decided to remove the failed WPA in order to repair it on ground and repair it.

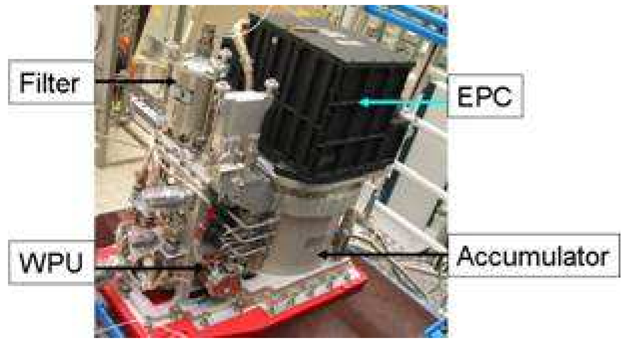

Figure 1: WPA Assy

On July 5th 2013 European Space Agency (ESA) astronaut Luca Parmitano replaced the failed WPA2 with the new WPA Flight Model 3 (FM3) and on May 18th 2014 the WPA2 returned to ground soft-stowed within Space-X3.

This paper describes the overall activities performed for the failure investigation, refurbishment and re-acceptance of the WPA2 Mk I.

III. On orbit investigation

Telemetries analyses showed that the Water Pump Unit (WPU) did not start running after two "run" commands included in the pump switchover automatic procedure. Upon reception of "run" command the WPA software performs the following motor start up sequence: if the motor does not reach the expected speed (i.e. minimum rump up speed of 1600 rpm) the startup sequence is repeated until a maximum of three times (see Figure 2). If the motor starts successfully, the plenum inlet temperature control is activated (see Figure 3). At the beginning of the startup sequence the validity status of WPA telemetries is not valid, so a dummy value for the WPA telemetries is automatically generated by the Data Management System (DMS). The red circled in Figure 2 and Figure 3 show the spikes corresponding to the dummy values generated by DMS

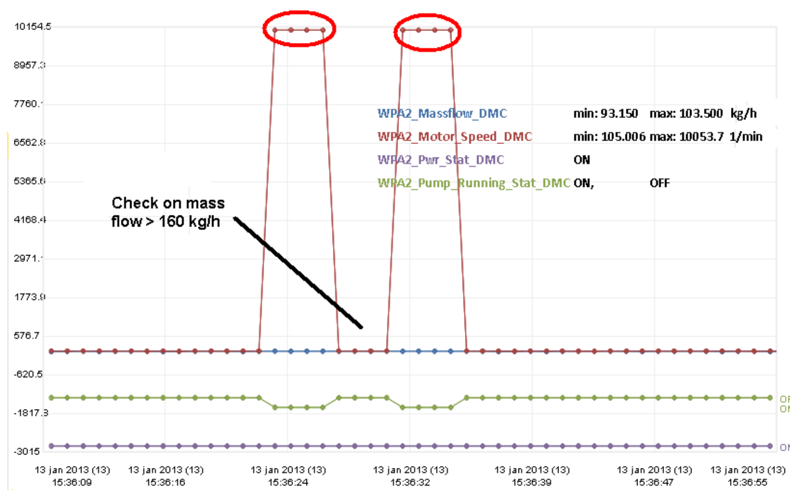

Figure 2: Anomalous WPU motor speed behavior

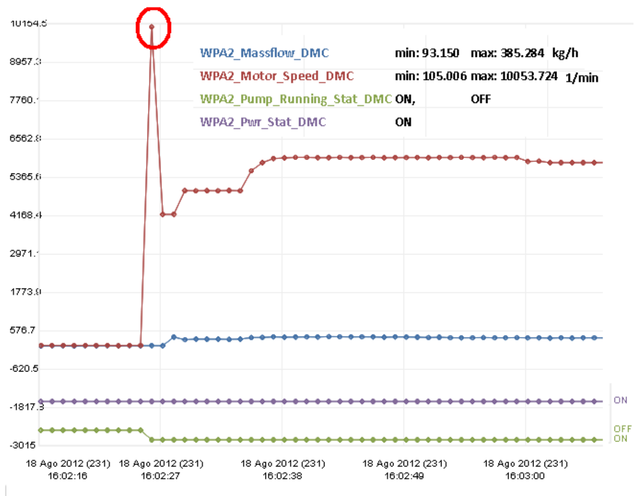

Figure 3: Nominal WPU motor speed behavior

WPA2 telemetries acquired directly by the Columbus vital system and therefore not processed by the WPA software confirmed that the WPU did not start running. In addition telemetries showed that the WPA2 (Electronic Power Converter (EPC) switched on nominally.

Potential root causes for WPU not starting have been identified as follows:

1. Hydraulic failure
2. Software failure during the stepper phase
3. EPC failure (e.g. Chopper Driver, Microprocessor Board, Motor Commutation Logic)
4. WPU failure (e.g. loss of motor drive due to open circuit or pump jamming)
5. Internal connector powering WPU failure

Please note that being the WPA Mark I a unique ORU, it is not possible to isolate the failure at EPC or WPU level.

As on orbit troubleshooting it was decided to perform multiple restarts of WPU isolating the WPA2 from the TCS loop (WPA2 was hydraulically short circuited using a jumper and WPA1 was kept running), to oversample the Power Distribution Unit (PDU2_WPA2) current and to mate and de-mate J1 connector before commanding the WPU. The analysis of oversampled data confirmed that the WPU did not start running and excluded the hydraulic failure. Software failure was judged not credible considering that before the troubleshooting the WPA2 was kept switched off and that the duration of each attempt was consistent with motor start up sequence. An internal connector powering WPU failure was excluded after crew inspection and connector de-mating/mating.

Finally the failure was identified as electrical and located in the EPC or in the WPU (electric motor, see Figure 4). No failure isolation at EPC or WPU level was possible, so Engineering recommended the WPA2 download for the following reasons:

1. Ground investigations to exclude a WPU common cause design failure potentially affecting WPA Mk II
2. Re-utilization of WPU and filter as ORU for WPA Mk II
3. WPA2 refurbishment as an additional Mk I spare, if needed

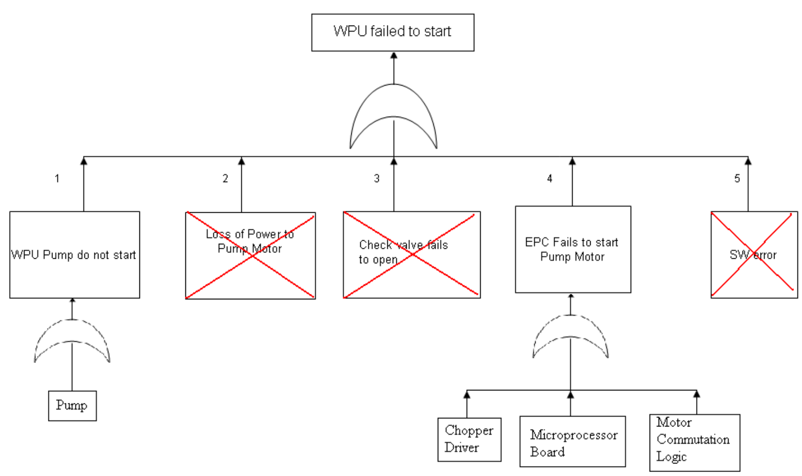

Figure 4: WPA Failure Tree

IV. WPA return on SpX3

The need to have a WPA unit spare or spare parts ready to be used until WPA Mk II availability induced the European Space Agency to decide for the return on ground of the failed WPA2.

The WPA would be returned with SpX3, inside a bag, soft stowed. In this configuration, the risk of a potential damage during descent was real because the WPA was designed and qualified for flying in hard mounted condition: this condition was therefore the only certified transportation configuration in which WPA design safety could be considered robust & reliable. Moreover additional static analyses simulating the new transportation condition could not be performed, due to the unavailability of a WPA Finit Element Model (FEM). Because of its big dimensions (608.83 x 409.73 x 831.92 mm) and huge mass (about 80 kg), the WPA has been packed inside a (M01) bag and with the Launch Authority it was decided to accommodate the bag in the Central stack of Dragon Pressurized Compartment (see Figure 5).

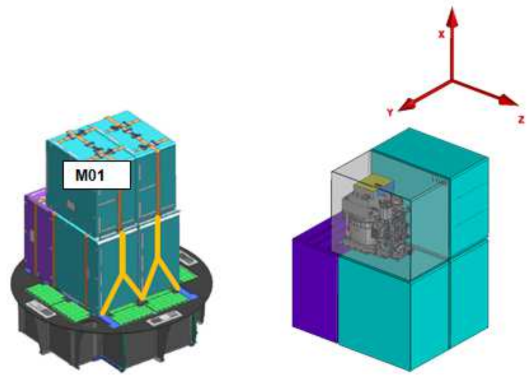

Figure 5: WPA Accommodation

TAS-I support was requested to identify the more critical areas of the pump and suggest possible work-arounds to mitigate and contain the risks of a WPA2 structural failure. To evaluate the foam pressures induced from the vehicle on the WPA inside the strapped bag, a general strength assessment, based on simple methods, was performed, by using all the phase C/D documentation. The assessment, while confirming the general WPA mechanical compatibility vs. Dragon requirements, highlighted some potential criticalities relevant to the WPA Quick Disconnect (QDs), sensors and piping: if the WPA flew in wet condition, potential leakage could not be excluded and the expected leakage would be in the order of 6 liters.

Figure 6: T-shirts placement (in contact with delicate parts of WPA)

Consequently, it was necessary to assure an appropriate packaging in order to limit, as much as possible, the leakage inside Dragon Compartment: all the sensors, piping and delicate parts of WPA should avoid contact with the foam. For the final packaging, in addition to the foam, the astronauts used also absorbent materials (dry wipes/T-shirts, see Figure 6).

A major point was relevant to the concern of a pump damage during the off nominal return; once the WPA was ready for downloading, it was clear that additional damage during the return could hamper the analysis of the anomalies occurred on orbit.

On GMT 138-2014 (May 18th), SpaceX3 Dragon Capsule splashed down in the sea. A preliminary visual inspection of the WPA performed at CMC (Houston), excluded further damages due to the transport. On 25th of July, a detailed inspection was performed by TASI PA to verify and integrate the preliminary NASA conclusions. The WPA FM2 was found in a good condition and neither leak nor visible damages were detected. The on ground investigation could start.

V. On ground investigation: failure localization and repair

The on orbit investigation had already excluded any hydraulic problem, therefore the on ground investigation was focused on identifying where in the WPA an electrical issue occurred. The activities were divided into two main parts: the former was related to failure localization and discrimination among the WPA components (mainly WPU and EPC), the latter was an in-depth failure investigation on the component identified as failed by the first phase outcome.

Phase1

The first phase implied high level functional checks just to either exclude or confirm the problem in the specific item object of the check. The activity was divided in 4 sequential steps: Step 1 – Activation, Step 2 – Harness check, Step 3 – WPU check, Step 4 – EPC boards check (see Figure 7).
The sequence of the checks was conceived to identify unambiguously in which part of the assembly the problem had arisen, in particular discriminating between motor (WPU) or electronic box (EPC) that were the most likely candidates. The tests were performed using standard laboratory electrical instrumentation and a ground DMS Emulator to simulate the Columbus DMS for command sending and telemetry acquisition. The 4 steps will be described in detail hereafter.

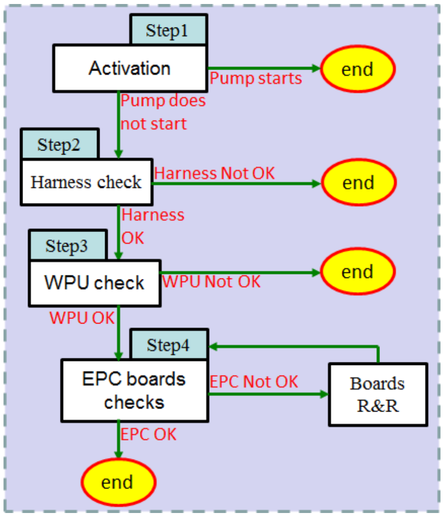

Figure 7: Troubleshooting Plan

Step 1 was just a first attempt to start the WPA in the same configuration as the on-orbit troubleshooting, i.e. connected to the hydraulic jumper to simulate a stand-alone closed loop. The aim of test was to replicate and confirm the on-orbit anomaly. The pump starting command was sent several times and the impeller did not start as expected. General telemetries were in line with on orbit data. The anomaly was then replicated and confirmed also on ground.

Before proceeding with dedicated tests to identify whether the problem was in the WPU or in the EPC, Step 2 was performed just to exclude that the failure could have been occurred in the harness and/or connector between the two items. This was done executing standard electrical continuity and isolation checks. Test results were judged compliant with requirements and acceptance values, then a failure in the harness was excluded and the investigation continued with the following steps.

In order to confirm or exclude a failure at WPU or EPC level, a Pre-integrated Development Item (PDI) model of the WPA was introduced in the test set-up. The PDI is a ground development assembly that reproduces exactly in terms of interfaces and components the flight WPA, allowing to test potentially failed flight WPU and EPC using functioning WPU and EPC of the PDI. This was done cross-connecting flight and ground items and commanding the activation of the impeller. In particular, in Step 3 the flight WPU was checked connected to the PDI-EPC (see Figure 9) and in Step 4 the flight EPC was tested connected to the PDI-WPU (see Figure 8).

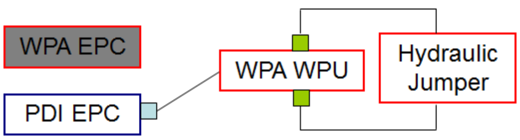

Figure 9: Step3 Test Set-up

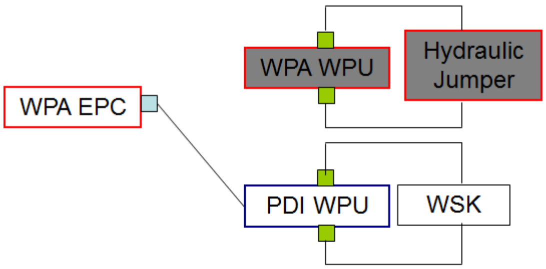

Figure 8: Step4 Test Set-up

Practically the test of Step 3 was the same as that of Step 1, with the only difference that the EPC was not the flight one but the PDI one. In this configuration, the flight WPU could be commanded with a working EPC allowing to immediately establish if the motor had failed or not. The outcome of the test was positive in the sense that the flight WPU started running when commanded trough the PDI-EPC. Telemetries were also in line with expected data considering the jumper closed loop configuration. This allowed to exclude a WPU electrical problem and to locate the failure definitely in the flight EPC.

The investigation was then focused on the EPC that was tested in Step 4. The test was performed connecting the PDI-WPU to the flight EPC. Given that the flight WPU was verified to be functioning in the previous Step, it was not used in this test to avoid any risk of further damaging the flight hardware. The use of PDI-WPU implied the introduction in the test set-up of the Water Service Kit (WSK) ground facility to simulate the Columbus water loop connected to the WPU. A preliminary check was done commanding to start the impeller in this configuration, and the expected non-starting outcome confirmed then the localization of the problem in the flight EPC. Then the test continued trying to identify which one of the removable EPC boards could be the failed one. A preliminary fault tree analysis had already identified 3 potential candidate boards that could have caused this type of WPA failure (i.e. impeller not starting): Motor Commutation Logic, Chopper Driver and Microprocessor. The intention of the test was to remove and replace each of them one by one with the available corresponding spare board and then command the WPU to start in order to identify the failed board. Unfortunately this approach did not allow to immediately detect the issue, because when the spare Chopper board was inserted in the EPC, the current limiter shut down all the equipment. This behavior was unexpected and then it was decided to orient the investigation towards the Chopper board. This last Step concluded the first phase of general testing that allowed to locate the failure in EPC excluding any problem in the WPU.

Phase2

The second phase of the activity was to perform an in-depth investigation of the Chopper Driver board.

The FM Chopper Driver was firstly studied with the use of X-ray investigation. This method allowed to discover a disconnection on the current regulator circuit that blocked the signal for the step down converter which delivers the supply voltage to the pump motor. One circular crack near a cathode was the most possible root cause for this disconnection (see Figure 10).

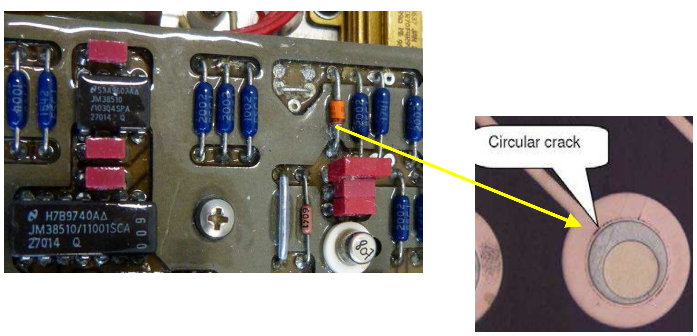

Figure 10: circular crack near CR5/cathode

On this base, it was agreed to put an additional connection via an additional wire in order to restore the lost functionality. Moreover, no indication for damage or overstress of other parts on this board has been found. No other FM boards were affected by a failure.

In order to verify the assumption of FM Chopper Board failure it was chosen to compare its behavior with the spare Chopper Board behavior, keeping in mind that the spare board had never been integrated in an EPC unit and had never done any environmental test campaigns, but only electrical and functional test at board level. In addition during the inspection and investigation it was found that the isolation of the connector was failed. So a recovery action was also in this case considered necessary. Finally, the functional tests have also shown a current Limiter intervention at Stepper mode to Brushless mode transition.

The troubleshooting activity continued at both FM and spare Chopper board level. The first activity was to re-establish the isolation of the connector case from GND_C of the spare board that during the test evidenced anomalies in the isolation value. Probably due to a workmanship error, the connector supports were not isolated from GND_C, therefore when the board was integrated in the EPC unit, this specific ground was connected to the chassis.

After this repair, a specific activity has been performed to understand and eliminate the differences found during Chopper FM and spare testing. At the end, a test to verify the repaired items and to verify the obtained equal behavior between FM and spare boards was performed.

The activities of visual inspection were made with the purpose to check the Chopper driver board EEE parts mounted on the boards and to identify FM and spare differences as well as the mechanical/weight differences. It was found:

COMPONENTS	CHOPPER BOARD FM	CHOPPER BOARD SPARE	REMARKS
R45	**15.4 KΩ** Correspondents to 14A level	**10 KΩ** Correspondents to 19,5A level This caused an unexpected EPC switching OFF by the Current Limiter, caused by the 19,5A threshold	For the "SET MOTOR CURRENT" signal the value of the resistor defines the value of the max. current value before … (PWM) shutdown. Adjust the maximum motor current at 14A by the threshold of the PWM shutdown signal. It was replaced on the spare board.
R46	**499 Ω**	**750 Ω**	It Influences the calibration of the output current provided to the motor on the basis of the Motor current setting. The calibration could be acceptable, but to avoid further re-calibration phase it was replaced on the spare board.
R59	**10 KΩ**	**15.4 KΩ** The resistance exchanged on FM spare (15.4 10 KΩ with 10 KΩ) is caused by workmanship at the assembly phase. Further explanation is not possible because the manufacturing documents are not available.	The Resistor is the protection on the PWM input and it has not influence respect any calibration or with negligible effects. The replacement was not mandatory but was performed anyway on the spare board.

On the other components no further differences have been detected. Please note that some components were not checked because they were not accessible or the printed reference on the components was not visible. As far as the weight measurements are concerned, those were compliant with the expected value.

The test performed on the two boards showed that for FM the current is limited at 14A, whereas for FM spare the current is limited at about 20A.

As conclusion of the activities of inspection, test and analysis, it was found that:

a) R46 in the Chopper board spare had to be replaced with a resistor of 499Ω in order to have the identical calibration as the chopper boards FM and spare.
b) Concerning the shutdown threshold, the WPA different behavior at the pump start between EPC +Chopper FM and EPC + Chopper spare was due to the exchange of the resistors (R59 with R45). R45 had effect on the PWM shutdown threshold and so it caused an unexpected EPC switching OFF by the Current Limiter. These resistors had to be exchanged in order to have also for Chopper spare board the maximum motor current protection at 14A instead of 19.5A.
c) Since during visual inspection not all components had been checked (about 15% of total EEE) because they were not accessible or visible and this test campaign at board level was not able to check completely the calibration of the system, it was necessary to perform the functional test at system level to be sure that the problem was solved completely.

   On the base of above inspection, test and analysis, finally the following reworks have been implemented in the chopper boards FM and spare. For the Chopper board FM, it has been reworked, restoring the interrupted path by a wire connected between CR5-cathode and LK3 jumper. To restore the connection by the external wire it was: dismounted the Printed Circuit Board (PCB) from mechanical frame; performed visual inspection in order to verify the possibility to connect the wire to the lead of the diode at the bottom side of the PCB according to the Flight rework rules; connected the wire; performed visual inspection on all soldering; performed the local coating treatment and check again the functionality of the chopper board. For the Chopper board spare, it has been reworked exchanging R45 with R59 and replacing R46 from 750Ω to 499Ω.

After reworking the conclusive tests have been carried out on both boards.

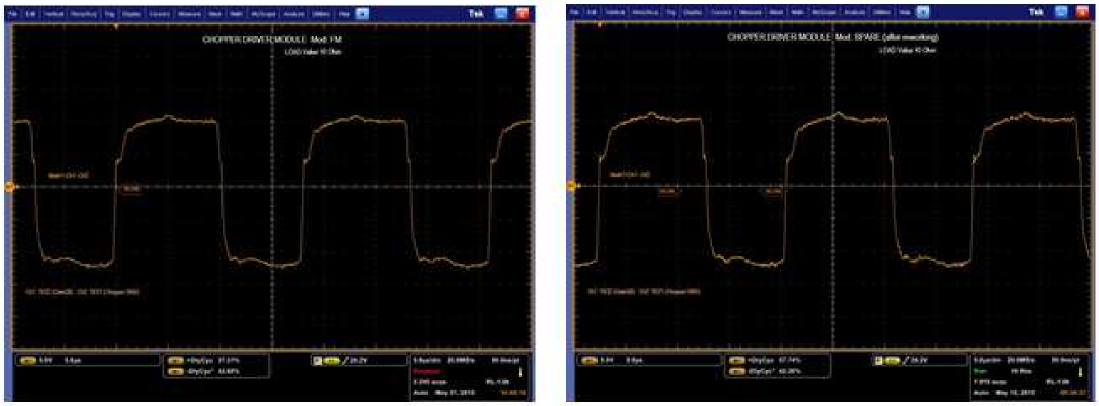

Figure 11: FM and Spare Chopper Board Voltage Behaviors

These tests have shown that after reworking the chopper boards FM and spare have the same behavior. Voltages measured along low voltage level circuit at open loop are quite identical between both boards (see **Error! Reference source not found.**). So also for the high voltage circuit in the closed loop. Both boards could be mounted on the WPA EPC FM for final acceptance test after board repair. However, the Material Review Board (MRB) has directed to mount the spare Chopper Board on the WPA FM2 Mk I. The EPC Integration of Chopper Board spare was then performed and the functional/electrical test outcome was that the WPA Mk1 worked correctly after the refurbishment.

VI. Re-acceptance test campaign

After refurbishment of the WPA with the spare chopper board, a re-acceptance test campaign was deemed necessary in order to have a WPA spare unit available in storage in case of in orbit unit failure.

Considering that a defined re-acceptance approach for this particular type of refurbishment (involving a replaced board inside an electronic box not removable from the entire assembly) could not be clearly derived from ECSS standards, two philosophies were proposed for discussion: acceptance tests at board level only with final functional test a WPA level, or acceptance and functional tests directly at WPA integrated level.

The first approach foresaw to perform standard mechanical (vibration) and thermal (including vacuum) acceptance of the spare chopper board only, given that this board had never been subjected in the past to environmental test campaigns. Then a final functional check at WPA level after board test was expected. The intention was to verify failure resolution and no workmanship errors of the board without overstressing other parts of the WPA not affected by the refurbishment. The second approach, instead, foresaw to perform a complete mechanical and thermal re-acceptance of the integrated WPA. The intention in this case was to verify the entire refurbished WPA in order to exclude additional damages induced by the return and troubleshooting phases.

The philosophy of the acceptance test at WPA level was explicitly recommended by ESA and was then endorsed by all parties through an MRB. The main stages of the re-acceptance campaign were the mechanical and thermal/functional tests.

Mechanical Test

For the mechanical acceptance, the definition of the environments and test configuration was a quite complex process. At the beginning the WPA was planned to be re accepted in hard mounted condition under a vibration level derived by HTV, Dragon, Cygnus Vehicles launch random scenarios. But only Cygnus & HTV environments seemed compatible with WPA qualification test levels for all the random spectrum frequency range. The necessity to exploit as much as possible carriers for a potential WPA uploading , led to decide for a vibration test in soft stowed condition. Soft stowed conditions in general represent a more benign environment w.r.t. the hard mounted condition, but in absence of a WPA FEM, only a test could confirm the adequacy of this new WPA launch configuration.

Due to its size, the WPA was put inside a M01 Bag and completely wrapped with foam layers of different dimensions. The vibration test campaign consisted in submitting the M01 Bag to three random vibration tests (one for each axis); the environment was an envelope of HTV, Dragon, Cygnus random profiles at acceptance level. In absence of test predictions, 3 intermediate random test levels were applied at different incremental levels in order to define, in case of need, a notching profile to not overcome the measured (output) PSD levels reached on the WPA items during the qualification test in hard mounted condition, in all the frequency range (see Figure 13).

The instrumentation plan was based on the plan already applied by the original supplier during the WPA Qualification Test, with additional sensors introduced for safety issues and a better monitoring of the Test Article (see Figure 12). The total acquisition channels were 57:

- 6 mono-axial accelerometer and 15 tri-axial ones placed on the TA
- 2 tri-axial one (pilot) placed close to the Belt Bracket and TA launcher interfaces

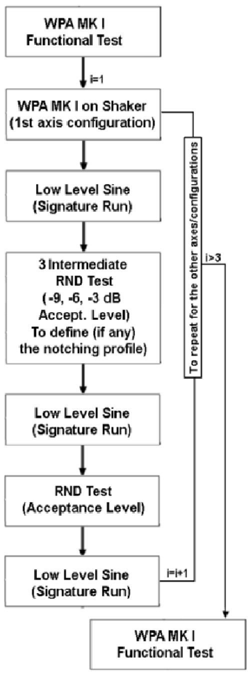

Figure 13: Test sequence

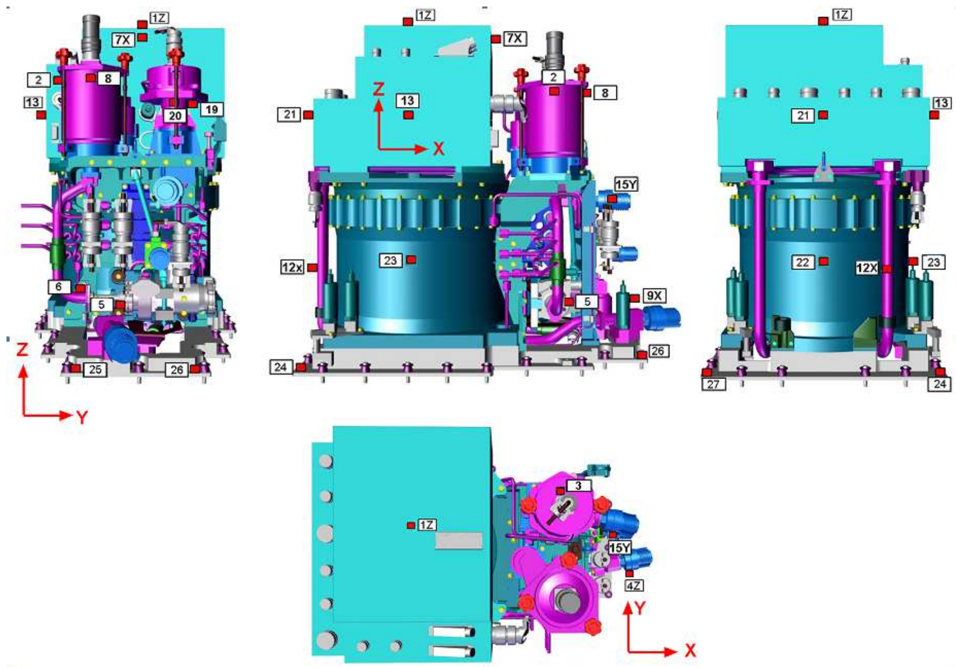

Figure 12: Instrumentation set-up

The M01 bag was constrained to the shaker through dedicated brackets to which the belts were fixed.

The WPA re-acceptance vibration test campaign results was considered successfully performed. Even if in the frequency range 20-50 Hz a manual notching was applied for all the three directions X-Y-Z, the input profile overall acceleration was in line with the nominal value (3.23 grms vs. 3.27 grms, see Figure 14).

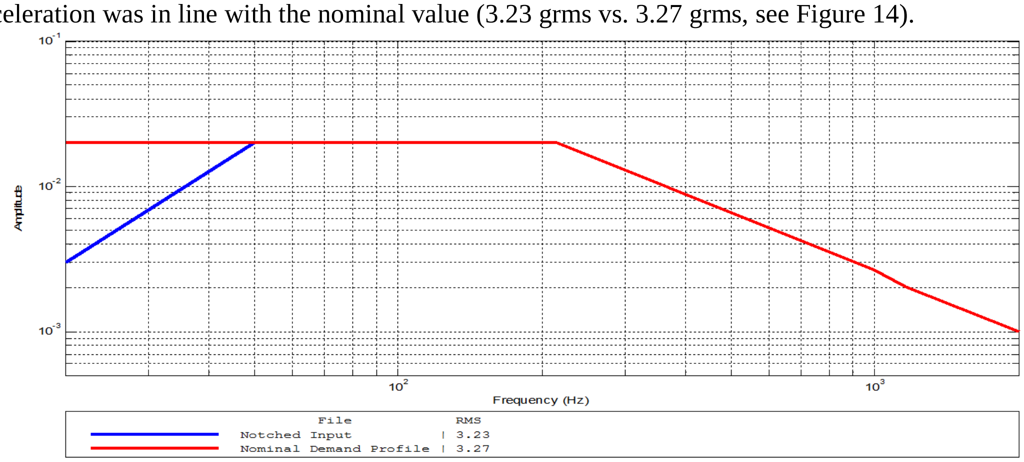

Figure 14: Test results

Low level sine sweep runs performed before and after each axis acceptance vibration run confirmed the absence of significant change in WPA dynamic behavior after each random vibration test, while the visual inspection confirmed the absence of evident rupture and permanent deformations on the WPA parts.

The go-ahead for the subsequent thermal and (hydraulic) functional acceptance could be provided.

Thermal Test

The thermal and hydraulic functional tests were defined according to the former acceptance campaign performed by the supplier of the WPA MkI. However, the temperature range could be reduced from the former 2-60°C to 12-40°C to take into account the real operative environment of the WPA onboard Columbus (see Figure 15). The reduced range was also intended not to further overstress the WPA hardware. Concerning the accumulator fill level, it was also decided to reduce it from the former 8 liters to 4 liters as a more representative level of the nominal average water quantity present in the WPA during on-orbit operations. The correct functioning of the accumulator bellows was confirmed during filling operation and following thermal/functional tests, in terms of repress/depress operations and compensation capability for thermal loads and flex hoses volume variations.

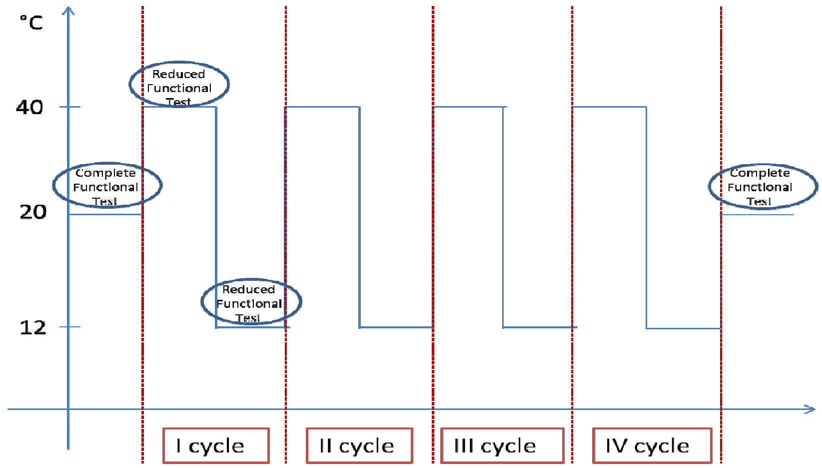

Figure 15: Test Sequence

Objective of the thermal test was to demonstrate that the WPA, and in particular the replaced Chopper board, could withstand the specified thermal cycles without any physical or performance degradation as evidenced by successful completion of intermediate and final functional performance checks. The test was performed in ambient by thermally cycling the water circulating inside the WPA in the selected range. A total of 4 cycles were executed with functional tests performed before and after the thermal cycling. Additionally, intermediate functional tests at the highest and lowest temperature were done during the first cycle. To demonstrate the correct behavior of the WPA and the success of the campaign, all recorded performance parameters during thermal cycling and functional tests were compared with either WPA on orbit telemetry values or former acceptance data.

All thermal cycles and functional tests were successfully performed with no anomalies in WPA behavior and hydraulic performances.

After successful completion of the re-acceptance campaign, the WPA was drained and then stored to be ready to be used as spare for the orbit unit in case needed.

VII. Conclusion

The activity investigation on WPA Mk I has been successfully conducted: the failure has been located and the WPA refurbished, the re-acceptance test campaign did not point out any anomalies. Moreover the WPA proved its robustness design during the SpX3 ground return inside a bag and the re-acceptance test campaign.