The European contribution to the investigation and preparation of a safe unmanned configuration for the International Space Station

Thomas Hiriart[1] and Lucas Marchi[2]
CAM Systems GmbH, Munich, 81377, Germany

Cesare Capararo[3]
ALTEC S.p.A., Torino, 10146, Italy

For more than 10 years, the continuous manned presence aboard the International Space Station (ISS) has allowed the scientific community to conduct a wide variety of experiments and has offered engineers a unique environment to test the systems that will be required to push forward the Human Space Exploration. On August 24th 2011, The Russian Progress 44 cargo spacecraft crashed in Siberia after its Soyuz rocket failed shortly after liftoff. More than a loss of supplies for the Space Station, this crash has threatened to put an end to an uninterrupted human presence in space over the past 10 years. Around the Globe, ground support teams have quickly faced the challenge to investigate and prepare the vehicle for a safe and sustainable configuration that would also allow continuation of scientific experiments, in the eventuality that the Expedition 29 crew comes back to Earth leaving an unmanned Space Station behind. In charge of the operations of Columbus - the European laboratory of the ISS - the European flight support teams have played a major role in defining and preparing a safe unmanned configuration for Columbus. The aim of this paper is then to discuss the main technical requirements that had to be met and the potential failure cases that have been envisaged. These aspects of the problem will be first covered from a thermal and life support systems perspective before being analyzed from a data management system point of view. Finally, beyond the strictly technical analysis, our hope is that this paper will demonstrate the energy and enthusiasm in facing the challenges encountered everyday by all teams in Europe involved in the Columbus project.

I. Introduction:

Following the crash of the Russian Progress 44 cargo spacecraft, the ground support teams around the globe have quickly faced the challenge to investigate and prepare the International Space Station (ISS) for a safe and sustainable configuration. This configuration should also allow continuation of scientific experiments, in the eventuality that the Expedition 29 crew comes back to Earth leaving an unmanned vehicle behind. Such investigations have already been performed in the past, especially after the fatal atmospheric re-entry of the Space Shuttle Columbia in February 2003. It is yet the first time that such an unmanned configuration is realistically envisaged since the Columbus berthing in February 2008.

The purpose of this paper is then to present the investigations, the risk mitigation assessments, and technical trade-offs that drove the definition of a safe Columbus configuration in preparation of an unmanned ISS period, and to enlighten the preparatory work accomplished by the ESA Flight Controllers and Support Engineers, and their NASA counterparts.

After a brief general introduction on the ISS and Columbus, Section 3 will introduce the need for technical assessments on an unmanned ISS configuration. Section 4 will focus on the Columbus required reconfiguration, presenting the main decisions and trade-offs made for thermal and environmental systems as well as for the communications and data management systems. Finally, Section 5 will be dedicated to the most interesting failure cases that have been assessed for an unmanned configuration in the scope of the Columbus operations.

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[1] COLUMBUS ECLSS/EPDS/TCS Flight Controller, Thomas.hiriart@cam-systems.de

[2] COLUMBUS DMS/COMMS Flight Controller, Lucas.Marchi@cam-systems.de

[3] COLUMBUS Flight Director, Cesare.capararo@altecspace.it

II. Background information on the ISS and Columbus:

A. The International Space Station:

The International Space Station is a unique manned vehicle, composed of more than a dozen compartments, flying higher than 300 km above the surface of the Earth and faster than 7 km/s.

Its purpose is to serve as a microgravity and space environment research laboratory in which crew members conduct experiments in biology, physics, astronomy, physiology and meteorology. It also offers a unique environment to test the systems that will be required to push forward human space exploration to the Moon or Mars. From an educational perspective, the Station provides unique opportunities by directly engaging students using radio, videolink and email.

The ISS is composed of 2 main segments: the Russian segment and the United States orbital segment (USOS). The Japanese laboratories (JLP and JEM), and the European module Columbus, while respectively controlled from Japan and Europe, are operationally considered part of the USOS segment (Fig.1).

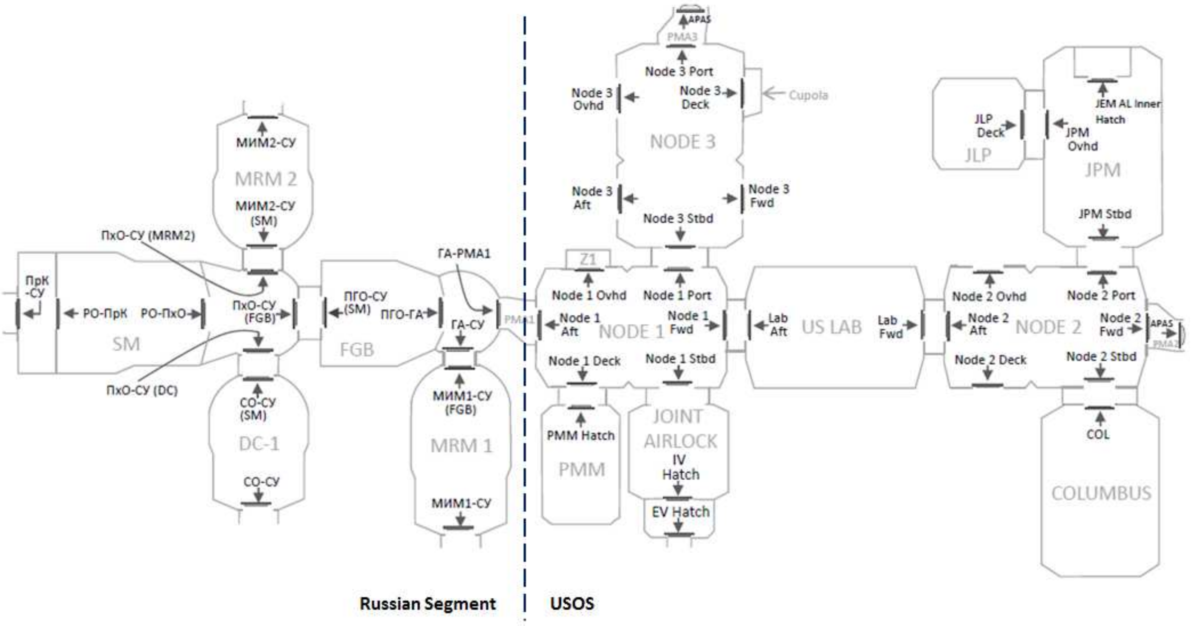

Figure 1. Schematics of the ISS pressurized/habitable volume[1]

In terms of responsibility, the ISS operates as an integrated vehicle with an integrated crew and a single crew commander. Each International Partner (IP) is responsible for controlling their module. The Columbus Flight Director has the authority to perform any mandatory and time critical action in Columbus while the Flight Director from Houston or Moscow, or the ISS Crew Commander (ISS CDR), has the final authority to take any necessary action required to ensure safety of the crew and the station.

There are typically 6 crew members continuously on-board the station: 1 Commander and 5 Flight-Engineers. Since the Shuttle's retirement, they take off per group of 3 from Baikonur in a Soyuz TMA, assume a 6-months tour of duty onboard the station, and come back to Earth in the same Soyuz. Typically, the crew works 5.5 days per week, performing science experiments and maintenance activities, exercising 2 hours a day, and holding public relation events.

While the Soyuz TMA is so far the only vehicle accredited for crew transfers, cargo supply can be achieved with the Progress M1, ATV, or HTV vehicles. These cargo supplies are critical to the success of the ISS operations since they provide propellant, crew consumables, water and oxygen, as well as science supplies.

B. Columbus, the European laboratory:

Flying since February 2008, the Columbus module is main European Space Agency's contribution to the ISS project. It is docked to Node2 (Fig. 1), at the forward-starboard part of the vehicle and can contain of up to 10 payload experiment racks and 4 external facilities which allows User Support Operation Centers around Europe to conduct zero-gravity research in a broad variety of fields (physilogy, biology, physics, astronomy).

The module is composed of 5 main technical subsystems, each of them being responsible for providing the ressources needed to achieve ESA mission objectives: assure safe environment for the crew, maintain vehicle safety, and allow efficient payload operations.

- Communications (COMMS):
  The COMMS system provides the necessary means to transfer data to and from the ISS. The Video Data Processing Unit (VDPU) is the interface and routing unit for video or high rate data coming from ISPRs or on-board Video Camera Assemblies (VCA). The High Rate Multiplexer (HRM) combines the columbus low, medium and high rate data into a single stream downlinked via Ku-Band.

- Data Management System (DMS):
  The DMS system is responsible for Columbus Emergency, Caution and Warning management as well as on-board monitoring and command execution. The Vital Telemetry Controllers (VTC) command the safing steps in case of emergency and are responsible for the data acquisition and monitoring of the vital layer (basic functionalities to maintain crew and vehicle safety in any scenario) . The DMS allows on-board file management thanks to the Mass Memory Unit (MMU). Failure detection, isolation and recovery is ensured by the Data Management Computer (DMC) while payloads are supported by the Payload Control Unit (PLCU).

- Environment Control and Life Support System (ECLSS):
  The ECLSS system assures a safe and comfortable atmosphere for the crew by controlling the cabin temperature with the Cabin Temperature Control Unit (CTCU), by removing the exedents of humidity in the Condensate Heat Exchanger (CHX), by efficiently mixing the air received from Node2 through the module using inter and intra-module fans, by monitoring the concentration of CO2 and O2 in the cabin via the use of additonal sensors and to provide the Smoke Detection functions.

- Electrical Power Distribution System (EPDS):
  The EPDS system provides electrical connection and power supply to all components of the module. Using 2 main Power Distribution Units (PDU), it converts and relays the power received from Node2 and offers through its outlets 120V and 28V connections.

- Thermal Control System (TCS):
  The TCS system provides active thermal cooling to the equipment mounted on cold plates and to the payloads racks. Via one single water loop, The Water Pump Assembly (WPA) circulates cold water throughout the module's pipes. The heat rejection is provided by 2 Interface Heat Exchangers (IFHX) located outside of Node2. In addition, the TCS system is responsible for maintaining the module shell temperature within the accepeted range (20°C to 23°C) during eclipse periods using 2 Heaters Control Units (HCU).

Each of these subsystems are monitored and controlled 24/7 by the Flight Control Team (FCT) personnel at the Columbus Control Center (COL-CC) located at the Deutsches Zentrum für Luft- und Raumfahrt (DLR, German Space Agency) in Munich. The FCT is also supported on a daily basis for anomaly resolutions and activity preparations by the Engineering Support Teams based in Turin and Bremen.

III. Needs for technical assessments on an unmanned ISS configuration:

A. Historical background:

In the wake of the Space Shuttle Columbia accident in February 2003, the impacts of a transition to an unmanned period (also called decrewing) were first assessed. The *ISS Decrewing and Recrewing Plan*[2] was generated to capture the processes, the timeline, and the high level priorities of such a transition and an official Flight Rule *B2-152 Crew Contingency Return*[3] was drafted to drive the adequate vehicle reconfiguration in preparation for an unmanned period. For information, a Flight Rule is a document that outlines the decisions planned in advance, and is designed to minimize the amount of real-time discussion.

In order to maintain these 2 operational documents up-to-date and applicable, the need of an event specific assessment has been quickly acknowledged. These assessments, driven by specific events, are based on the time available prior to the unmanned period, the new hardware on-board, the increment-specific vehicle configuration, and the current systems performances.

B. August 24th 2011, crash of the Progress 44 cargo vehicle:

On August 24th 2011, the Russian Progress 44 Cargo Spacecraft crashed in Siberia after its Soyuz rocket failed shortly after liftoff. More than a loss of supplies for the Space Station, this failure compromised the launch of future crews thus threatening to put an end to an uninterrupted human presence in space over the past years. The rockets used for cargo and for crew transportation indeed share some common propulsive stages and the failure that occurred on August 24th triggered heavy investigations on the use of the Soyuz TMA.

Following this unfortunate event, an Increment 29 specific version of FR B2-152 needed to be prepared and teams around the globe started to re-assess the feasibility of decrewing the ISS. An Increment is a term used for planning purposes, it starts when the departing crew leaves. This unit of time typically serves as a basis to plan maintenance activities and payload operations and is used by the different Flight Control Teams to coordinate their efforts. At beginning of Increment 29, when after 6 months on-board 3 crewmembers left the Station, the other 3 astronauts (Expedition 29) were planned to stay on board until November 2011, waiting for the next crew expeditions to take over. Durations of crew expeditions cannot be extended due to both medical constraints and technical limitations of the Soyuz capsules. Therefore the ISS would have been left unmanned, should the new Soyuz TMA launch be delayed to after Expedition 29 departure.

IV. Increment 29 unmanned ISS preferred configuration:

A. Programmatic priorities and principles for the definition of an unmanned configuration:

As a first step, it is important to understand the programmatic priorities and the governing principles taken into account while discussing the technical details of an unmanned configuration. These priorities and principals are described in Table1.

Table 1. Priorities and principles for ISS decrew scenario

Programmatic Priorities
1) Maintain vehicle safety
2) Maintain sufficient insights into vehicle health status
3) Maximize critical systems redundancy
4) Prevent loss of critical hardware
5) Prevent loss of science
6) Optimize vehicle configuration for an efficient return to nominal operation
7) Continue utilization

Governing Principles
1) Minimize fire risks by powering down non-essential equipment
2) Terminate ventilation to decrease fire propagation risks
3) Protect for debris collision risks by closing hatches

Yet, these principles are not to be seen as strict constraining rules and emphasis on payload experiments could be a driver for trade-offs between risks mitigation and ISS utilization. As we will see in the next chapter, many of these trade-offs have been made in order to allow as much as possible payload operations while maintaining vehicle safety to the highest level. And as we go through these trade-offs, we will try to justify them referring as much as possible to the priorities and principles.

B. A new baseline for Columbus in case of an unmanned ISS:

This section aims at presenting and explaining in an understandable manner the changes brought to the Columbus baseline by the absence of crew on-board the station. A complete and exhaustive review of all changes and discussions would be rather long, but we will here present the major points that led to operational trade-offs for the ECLSS, TCS, DMS and COMMS subsystems. If necessary, and in order to understand the roots and implications of such baseline changes, a more detailed explanation of each system will also be provided.

1) ECLSS system unmanned configuration:

a. The ECLSS System:

The Environment Control and Life Support System ensures the air revitalization function in the module. The air is carried from Node2 into Columbus via the Inter-module-ventilation Supply Fan Assembly (ISFA); it circulates in the module thanks to the 2 Cabin Fan Assemblies (CFA) and is then returned to Node2 by the Inter-module-ventilation Return Fan Assembly (IRFA) (Fig. 2).

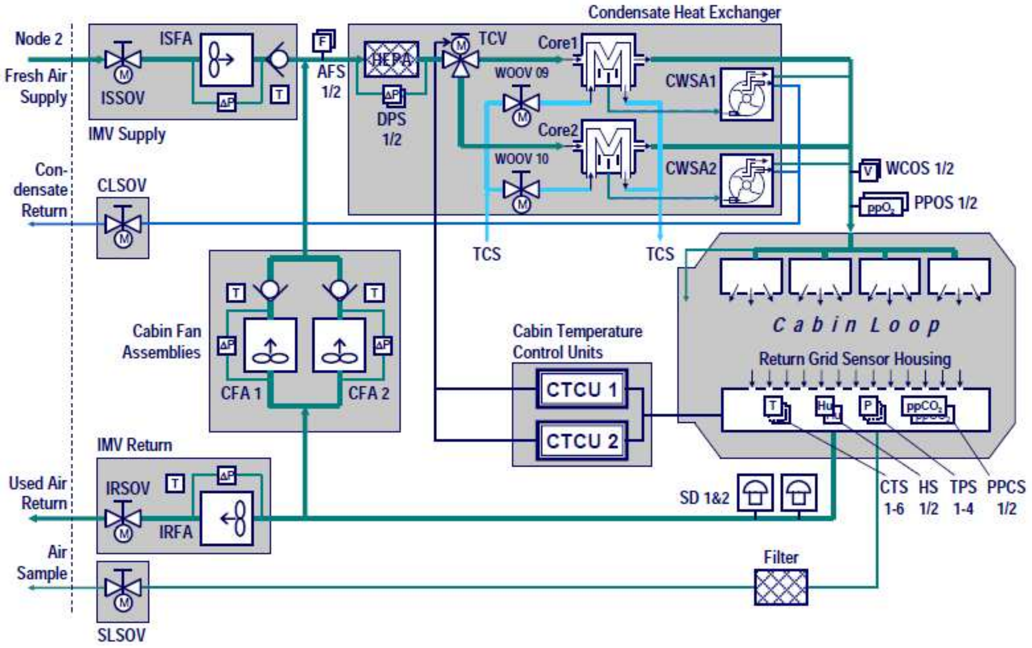

Figure 2. Columbus Environmental Control and Life Support System (ECLSS) [4]

The Condensate Heat Exchanger (CHX) is regarded as an important piece of the ECLSS system since it provides cabin temperature and humidity control. Within the CHX, the Temperature Control Valve (TCV) distributes the air coming from the CFA and ISFA into two paths: one where the air goes through a water-cooled heat exchanger (Core) and another path where the air remains at ambient temperature. The percentage of air going through the cold Core is regulated by the movement of the TCV, itself controlled by the Cabin Temperature Control Unit (CTCU). The cabin temperature set point can be commanded from the ground or by the crew. The goal is to keep the cabin temperature in the thresholds defined by the crew comfort zone 18-28°C. In function of the temperature of the water going through the Core, a fraction of the air will be cooled and the water vapor will condense. The condensate is collected by a Condensate Water Separator Assembly (CWSA) and delivered outside Columbus via the Condensate Return line. The condensation products of all the USOS modules are collected in the Node3 module and transformed to potable water in the Water Processing Assembly (WPA), under NASA responsibility.

In addition, the composition of the air in the module is accurately monitored via a broad range of sensors measuring the levels of oxygen, carbon dioxide, and humidity while potential fire sources can be detected by 2 Smoke Detectors (SD).

In terms of pressure management, 4 Total Pressure Sensors (TPS) continuously measure the pressure of the air in the cabin. In case of an overpressure, the Positive Pressure Relief Assembly (PPRA), if enabled, is able to vent some atmosphere overboard when the pressure becomes higher than its cracking valve limit. In nominal condition, the PPRA is disabled and the overall ISS pressure control is mediated by the central functions of the US Lab and Node3, since all modules normally are not isolated. The Columbus PPRA can be commanded enabled from the ground when the module is isolated.

b. Modifications brought to the Columbus ECLSS baseline:

Before the Increment 29 specific investigations, the traditional unmanned configuration foresaw the Columbus hatch to be closed, and all its fans (ISFA, IRFA and CFA) to be turned off to mitigate and decrease the propagation of potential fire sources (Governing Principles, points 1 and 2). Yet this configuration of the fans would triggers some consequences impacting negatively the operations not only of the module but of the whole station.

First of all, the inter-module ventilation allowing the air to be homogenously revitalized between all the USOS modules would be lost. After the unmanned period, having a homogeneous atmosphere throughout the stack would considerably ease the return of the crew (Programmatic Priorities, point 6). Mixing the air between the different modules also allows NASA to use the Columbus sensors to have a redundant insight into the atmosphere composition of the station (Programmatic Priorities, point 2).

Moreover, by switching off the CFA, the cabin temperature can no longer be efficiently maintained, and even more impacting, the cabin smoke detection is lost. As a result, all air-cooled equipment and equipment relying on the cabin smoke detectors, such as payload racks, would need to be powered off. Continuing utilization and avoiding loss of science being one of the priority (Programmatic Priorities, points 5 and 7), it was decided to allow the CFA to remain powered on and for the above reasons, the ISFA and IRFA to remain available for inter-module ventilation. This was also supported by the confidence gained, after more than 10 years of ISS operations, on the reliability of the air fans, originally thought as one of most credible source of fire.

As mentioned in the previous section, the CWSA is responsible for collecting the condensate water separated from the air in the Core, thus providing an efficient removal of the excess of humidity. The main contributor of humidity aboard the station being the crew, in an unmanned configuration, the humidity will be naturally lower. It was then agreed among International Partners that collecting condensate in only one module would be enough to regulate efficiently the humidity along the USOS. It has conjointly been agreed to condense and remove humidity in the Node2 module and that all other USOS modules would stop condensing.

As a result, the need for humidity removal in Columbus becomes obsolete and no rational sustains having an active CWSA in the module since fire risks are to be minimized by powering down non-essential equipment. A downside effect of not collecting condensate in the module is that condensation must then be avoided at all cost. In the event that the air would form condensate in the Core, without being removed by an active CWSA, it would trigger bacterial growth which could deteriorate the hardware in the long term. This point has triggered some reconfiguration on the thermal system, and is discussed in the next section.

2) TCS system unmanned configuration:

a. The TCS System:

The Columbus internal thermal control system is composed of one single water loop (Fig. 3). The core of the system is the Water Pump Assembly (WPA). For redundancy purposes, there are 2 WPAs connected to the loop, but only one is active at a time. The goal of the WPA is not only to circulate the water through the system but also to regulate the temperature of the water at different points of the loop via the use of Water Modulating Valves (WMV). In function of the temperature readings of the Water Temperature Sensor Blocks (WTSB) and of the set points commanded from COL-CC, the active WPA will automatically move the WMVs to meet the temperature target.

The heat is collected at the “Plenum” which consists of payload experiment racks and system equipment cold plates. The heated water is then carried to the 2 Interface Heat Exchangers (IFHX) allocated to Columbus. The heat is then distributed to External Thermal Control System (ETCS, under NASA responsibility). When the warm water goes through the IFHXs, the heat is transfered into an ammonia circuit located outside of the station. The heat transported by the ammonia is then dissipated via radiators.

To provide some general ideas about water temperatures throughout the loop, the water is at around 5°C after being cooled when going through the IFHXs (WTSB6 level). It is then warmed up using WMV3/4 to reach 7°C at the Condensate Heat Exchanger (CHX) (WTSB3/4 level). The set point at the WTSB1/2 level, inlet of the plenum, is set to 17°C, and the water is at about 22°C after having collected heat in the plenum.

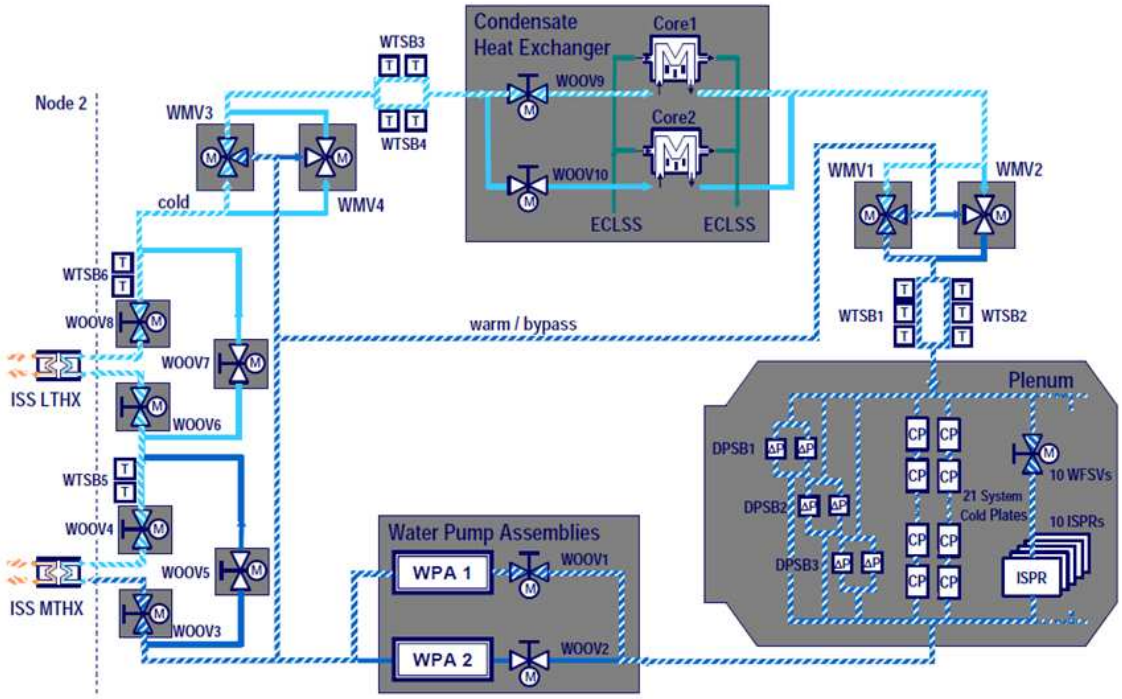

Figure 3. The Columbus water cooling loop[4]

b. Modifications brought to the Columbus TCS baseline:

As discussed in section 4.2.1.2., condensation in the ECLSS Core needs to be avoided at all cost since the CWSA will be powered down. The presence of condensate in the Core without an active condensate collection would trigger deposits and bacterial growth which could deteriorate the hardware in the long term and compromise air quality for a safe crew return on board.

The condensation in the Core depends on two parameters: the CHX inlet water temperature and the cabin dew point. As mentioned earlier, the CHX inlet temperature is set by COL-CC (usually around 7°C) and automatically regulated by the WPA using WMV3/4. The cabin dew point depends on the cabin temperature and the humidity rate (Eq. 1: August–Roche–Magnus approximation); it is in nominal conditions around 9°C.

The dew point of the cabin air in °C, given the relative humidity *RH* in percent and the cabin air temperature *T* in °C, is obtained by the following formula**:**

$$Dew\ Point = \frac{b * \gamma(T,RH)}{a - \gamma(T,RH)}$$

$$\gamma(T,RH) = \frac{a * T}{b + T} + \ln\left(\frac{RH}{100}\right)$$

$$a = 17.271$$
$$b = 237.7°C \qquad (1)$$

In a nutshell, the cabin dew point determines the air temperature at which condensation would start. Then, the only way to strictly ensure no condensation in the Core is to set the CHX inlet temperature set point higher than the dew point with sufficient margin to account for natural fluctuations. After further investigations, it was agreed that a CHX inlet temperature of 10°C will comply with this requirement at the condition that the cabin air is dry enough, which would sufficiently lower the dew point in Columbus.

Since it was decided to drive the condensation in Node2, the equivalent of the CHX inlet temperature needs to be significantly lower in Node2 than in Columbus. This would guarantee the absence of condensation in the Columbus Core. Nevertheless, there is a risk of electrostatic discharges if the relative humidity is too low. As a result, NASA will set their Node2 equivalent of the CHX inlet temperature such as the relative humidity is around 25%, which protects both against microbial growth at high relative humidity and electrostatic discharge at low relative humidity.

Yet, coming back to Columbus, the CHX inlet temperature set point cannot be set that high without consequences. Some mandatory maintenance activities, performed from the ground during an unmanned period, would indeed require a CHX inlet temperature a 5°C. By forcing the set point to be around 10°C, we would prevent these important maintenance activities from being performed. One of these activities consists of doing a WPA switchover between the active and the passive (redundant) pump once every 3 months to ensure the correct reconfiguration of the valve inlet of the passive WPA and therefore ensuring the availability of the passive pump in case the active one fails. In other words, the activity is needed to ensure redundancy. It precisely corresponds to point 3) of the programmatic priorities defined for an unmanned period. A trade-off is then needed.

The final decision, agreed to by ESA and NASA, has been to set the CHX inlet temperature to 10°C, but to allow temporary decreases down to 5°C to allow maintenance activities to be performed from the ground. Obviously, during the short period of time at 5°C, some water condensate will form in the Core. But with the fans (ISFA and CFA) active, this condensate will evaporate relatively quickly without causing any hardware damage. This trade-off allows both a dry Core, clean of microbiological growths, and a cycling of the valve inlet of the passive WPA, guarantying an effective pump redundancy. In parallel, NASA will maintain the relative humidity in Node2 around 25%.

3) DMS system unmanned configuration:

The data management system is needed for nominal Columbus monitoring and commanding in both manned and unmanned configuration. All computers are cooled via cold plates and do not need to be reconfigured in case of decrewed ISS. However in the unmanned case, the crew interfaces (mainly laptops) are useless and will be powered off, especially the two portable workstations (PWS). One PWS will be moved to the other side of the Columbus hatch in Node 2 to facilitate ingress of the module in a re-crew scenario. No other laptops will be active in Columbus. The Payload Ethernet Hub Gateway (PEHG), which shares Columbus Audio Terminal Unit 2 (ATU2) power feeder, will be nominally deactivated. On-demand activation will be performed if the PEHG is required to support NASA payloads in Columbus.

4) COMMS system unmanned configuration:

Nominally, only the Video Data Processing Unit (VDPU), the High Rate Multiplexer (HRM) and both Audio Terminal Units (ATU) are active in Columbus. The rest of the COMMS equipment such as Video Camera Assembly (VCA), Video Camera Recorder (VCR) or Video Monitor (VMN) are activated on demand from ground. Since ATUs are only used for crew communication, they will be deactivated in the unmanned configuration. The rest of the baseline will not be changed but crew will adjust both Video Camera Assemblies to capture the Columbus cabin in the field of view before leaving the station. This will allow the Flight Control Team to assess Columbus cabin situation when temporarily activating VCA from ground.

V. Contingency cases:

This section is dedicated to the many failure cases that have been assessed for an unmanned configuration. We chose to discuss the 2 failures cases that appear to be the most interesting in the scope of the Columbus operations. We will first discuss the eventuality of an ammonia leak emergency. We will then review the strategy for a loss of communication between the ground and the ISS due to a loss of S-Band.

A. Ammonia Leak Emergency Response:

There are 3 scenarios that have been granted the official title of *Emergency*: fire, rapid depress, and toxic release. Each one of these scenarios has been seriously re-investigated in the scope of an unmanned configuration. This section will focus on the toxic release case, and more precisely on the Ammonia leak scenario.

As already briefly mentioned, the USOS rely heavily on an external ammonia cooling circuit to collect the heat loads transferred from the internal water circuits to the ammonia via Interface Heat Exchangers. The ammonia loop then releases the heat to space by means of radiators. A rupture of one of these Interface Heat Exchangers is considered as a possible scenario and would be catastrophic for the crew and the station. The ammonia would spread quickly in the internal thermal cooling lines before diffusing into the cabin air. Only a small concentration of ammonia spread into the cabin would be lethal for the crew.

As soon as an ammonia leak is annunciated, either by the crew or by automatic detection via the Water Pump Assembly (WPA) internal sensors on board, the central computer of the station commands a series of automatic reconfigurations supposed to save the crew and the vehicle. Among others, the software commands the closure of the inter-module ventilation fans and their related valves in order not to spread any further the ammonia throughout the station. Yet, by doing so, since the hatch is closed and the Positive Pressure Relief Assembly (PPRA) function is nominally disabled, the ammonia concentration spreading in Columbus could build a disastrous overpressure.

Two options were then investigated: enabling the PPRA during the entire duration of the unmanned phase, or updating the on-board software triggering the automatic closure of the inter-module ventilation valves. The PPRA being not certified to regulate the pressure increase caused by an Ammonia leakage in Columbus or of a volume several times bigger than Columbus, it was decided to rather keep the Columbus PPRA disabled and to proceed with a software update to inhibit automatic modules isolation. In this configuration the centralized positive pressure control function of the US Lab and Node3 would vent any excess atmosphere coming from the ammonia leakage occurring in any of the modules stack. With the ISS unmanned, the risk of cross contamination between modules was considered less critical than the risk of compromising the structural integrity of the affected module.

B. Complete loss of S-band forward and return link:

1) Nominal commanding and telemetry via S-Band:

Commands between Col-CC and the Columbus module are sent via a complex and worldwide infrastructure. On the ground, they are routed through the Interconnection Ground Sub network (IGS) from Col-CC in Munich to MCC-H in Houston (Fig. 4). From there, they are forwarded to TDRSS ground terminals in White Sands and relayed by a TDRSS satellite to the ISS S-Band equipment, which delivers the commands to the ISS prime command and control computer. This computer filters the commands and forward only Columbus computers addressed commands to the Columbus module.

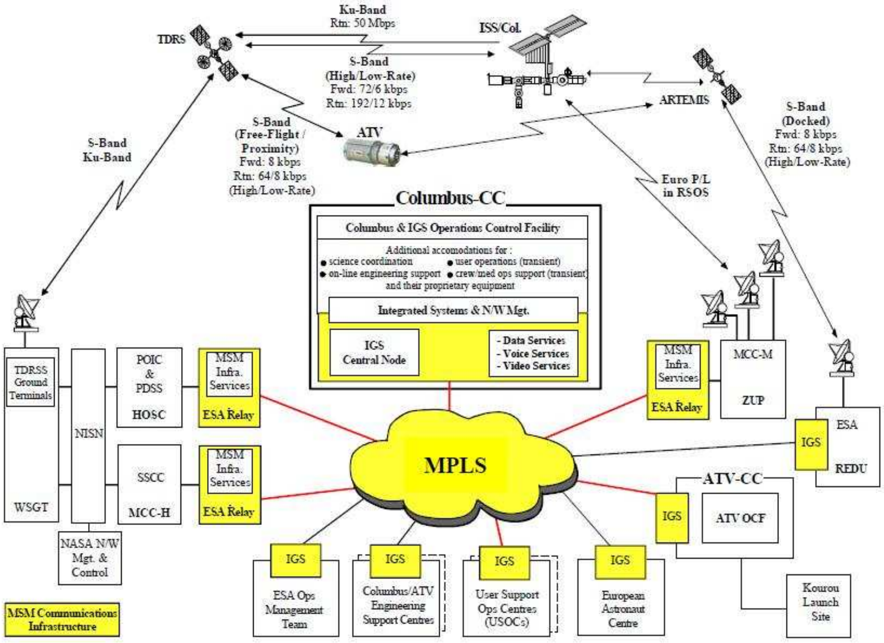

Figure 4. Ground Segment Overview[4]

A subset of Columbus telemetry, command responses and onboard event messages is downlinked via S-band. This telemetry is originating from the Mission Management Computer in Columbus and forwarded to the prime USOS Command and Control Multiplexer and Demultiplexer which packetizes the data for downlink via S-band equipment, TDRSS, White Sand and MCC-H. MCC-H delivers the un-packetized data to Col-CC through the IGS. The majority of Columbus telemetry is downlinked via Ku-band. The on-board path for this telemetry is different and does not relyon the ISS S-band equipment.

The S-Band equipment is redundant on the station but only one string is active at a time: S-Band string 1, located on Starboard Truss Segment 1, is nominally back-up and deactivated and S-Band string 2, located on Port Truss Segment 1, is nominally prime and active. In case of failure of the prime S-Band string, the back-up string can be used. If the back-up fails, the S-band link to the ISS is completely lost and with it the standard commanding capability.

ISS is not fully autonomous and requires human intervention to remain operational. When unmanned, commanding capability becomes therefore fundamental to minimize the risk of losing the vehicle. Alternative commanding capabilities were therefore assessed in the frame of the decrew assessments.

2) Alternative commanding via Ku-band:

The Ku-band link is and additional forward and return link to the station. Due to its high bandwidth capabilities, it has mostly been used to downlink data from the station. Until now, this has been the only usage developed for the Columbus module which uses Ku-band to downlink system and payload low and medium rate data as well as high rate data such as compressed video or payload science data.

However, new capabilities have been recently developed by NASA to use PCS from ground via Ku-Band. The operator on ground will actually remotely log into the onboard PCS and use the laptop's displays to send commands to other computers in the stations. The commands are not initiated from ground but from the onboard PCS (Fig. 5). Therefore, only the commands nominally available to the PCS could be sent.

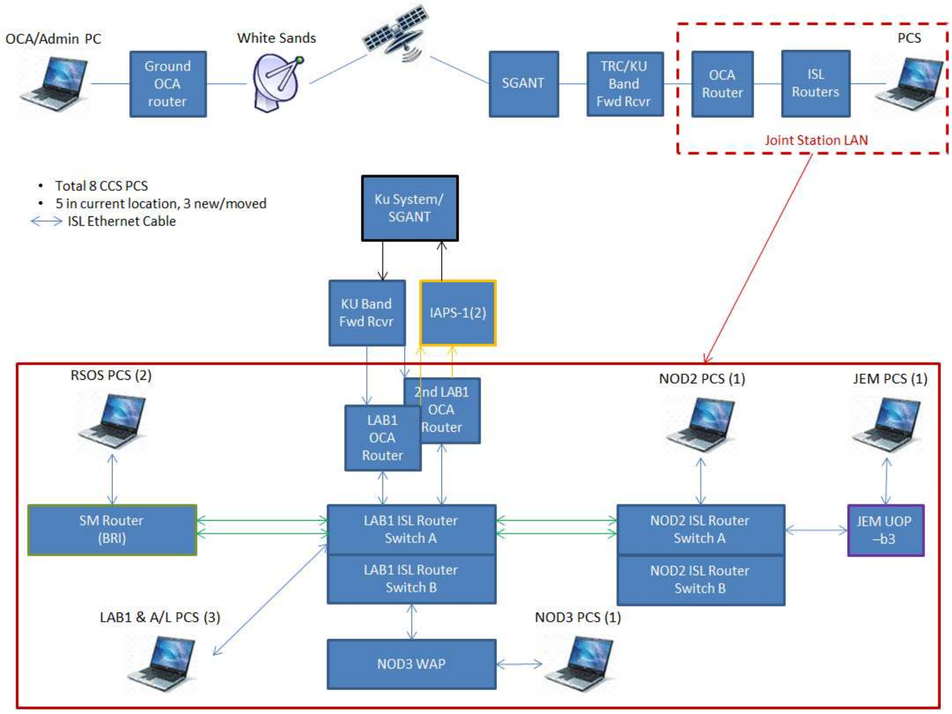

Figure 5. Commanding capabilities for the crew[4]

The subset of Columbus commands available in the PCS is limited to equipment safing and station mode reconfiguration. Therefore, it is not possible to command Columbus nominally using this method.

3) Commanding using Russian asset:

The Russian ground sites have the capability to send command or receive telemetry to or from the ISS Russian segment. The Russian data management system and the USOS data management system are connected on-board in order to perform some specific tasks (e.g. emergency response or attitude control).

There are 10 Russian Ground Sites (RGS) but only 3 of them have the capability to send commands during their pass. A Russian ground pass lasts from 10 to 20 minutes and there are 11 passes per day. The Russian daily commanding window is therefore limited to a couple of hours maximum. Since multiple commands cannot be sent at the same time, this window must be shared between the users, which are limited to Moscow Mission Control Center (MCC-M) and Houston Mission Control Center (MMC-H). MCC-H would not be able to send international partners (IP) commands via Russian Ground Sites. This is due to a limitation in the MCC-M command server concerning the identification of the command emission center. Unfortunately, the MCC-M Command server will only accept MCC-H commands identified as NASA commands. All Russian Ground Sites can receive telemetry, which means that the daily telemetry window lasts in total about 3 hours.

On top of these ground limitations, there are also on-board limitations due to the different design of the Russian and USOS data management systems. There are limitations to the MDMs that can be commanded (e.g. currently Node 3 cannot be commanded) and telemetry is limited to the American Contingency Format (ACT) which is a small subset of USOS telemetry that contains also Columbus essential telemetry. Data loads are possible through the RGS but not file uplinks.

4) Flight Control Team reaction in case of double S-band failure:

The Columbus Control Center is heavily relying on S-band forward and return link for nominal operations of the Columbus module. The loss of S-Band is a possible failure case which has been considered among the decrewed ISS failure cases. The loss of S-band return link will be compensated by the telemetry available via Ku-Band. An additional redundancy will be provided by American Contingency Telemetry received as part of the Russian telemetry. As explained in the previous chapter, the loss of S-band forward link cannot be worked around by commanding through the Russian Ground Stations.

A partial workaround will be available by commanding remotely PCS from ground via Ku-band. However, only a limited set of Columbus commands is implemented in the PCS. Therefore, in case of complete loss of S-band forward and return link, only very limited commanding will be available for Columbus. In order to respect the priorities for unmanned Columbus operations, the following was agreed to:

- After loss of first S-Band string: Columbus shall be configured in the simplest stable configuration:
    - Payloads will be deactivated or reconfigured so that they can stay “uncommanded” until recrew of the ISS.
    - Consideration will be given to ground-based preventative maintenance tasks which would be needed before recrew of the ISS
- After loss of second S-Band string, no more nominal Columbus commanding is possible:
    - All daily/weekly system tasks will be aborted (e.g. onboard log file retrieval or valves cycling.)
    - In case of anomalous condition requiring intervention, the only available commands would be the ones implemented in the PCS. In the worst case, Columbus will be commanded to the Berthed Survival Mode which is a safe configuration without any possible utilization of the module.

VI. Conclusion:

In the scope of this paper, the main decisions and trade-offs made for the Columbus thermal and environmental systems as well as for the communications and data management systems have been explained and justified with regards to the programmatic priorities defined by the ISS Program Management. Condensation management throughout the station and the need for continued ventilation between modules appear to be the key points driving most of the Columbus reconfigurations. In terms of failures management, the ammonia leakage case, as well as the other emergency scenarios, has received intense attention while the S-Band double failure has forced NASA and its partners to work on implementing a commanding capability via Russian ground sites.

On November 14th 2011, The Soyuz TMA-22 lifted off as scheduled from the Russian-leased Baikonur cosmodrome in Kazakhstan. Carrying one American and two Russians, it was the first manned vehicle launch following the Progress 44 crash. The launch successfully put an end to the threat of an unmanned ISS and the Expedition 29 crew never had to return to Earth leaving an empty station behind. Despite the happy ending, the amount of work accomplished by the support teams has not been performed in vain. As the Soyuz return to flight was very close to the deadline for Expedition 29 return, even some of the preparatory activities to configure the ISS for the unmanned scenario were conducted by the crew and from ground, as well as some tests to verify the required functionalities, such as for instance the above mentioned commanding capabilities via Russian assets.

All the reconfigurations on the Columbus systems discussed in this paper have been tracked into official operational documents that would be put in use if such a scenario were to happen again. The drivers for trade-offs between risks mitigation and ISS utilization have been well identified and discussed among International Partners while some results of the Increment 29 investigations are currently being developed and implemented.

References

[1] Schematics adapted from ISS Emergency Procedures Volume 1, p. E1-5E, 21 Dec. 2011, NASA
[2] SSP-50715, ISS Decrewing and Recrewing Plan, NASA
[3] ISS Flight Rule B2-152 Crew Contingency Return, NASA
[4] Schematics extracted from Columbus Crew Training Material – Courtesy of the ESA European Astronaut Centre