Inter-Module Ventilation Changes to the International Space Station Vehicle to support integration of the International Docking Adapter and Commercial Crew Vehicles

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The International Space Station (ISS) Environmental Control and Life Support System (ECLSS) is continuing to evolve in the post-Space Shuttle era. The ISS vehicle configuration that is in operation was designed for docking of a Space Shuttle vehicle, and designs currently under development for commercial crew vehicles require different interfaces. The ECLSS Temperature and Humidity Control Subsystem (THC) Inter-Module Ventilation (IMV) must be modified in order to support two docking interfaces at the forward end of ISS, to provide the required air exchange. Development of a new higher-speed IMV fan and extensive ducting modifications are underway to support the new Commercial Crew Vehicle interfaces. This paper will review the new ECLSS IMV development requirements, component design and hardware status, subsystem analysis and testing performed to date, and implementation plan to support Commercial Crew Vehicle docking.

Nomenclature

ISS	=	International Space Station
ECLSS	=	Environmental Control and Life Support System
THC	=	Temperature and Humidity Control
IMV	=	Inter Module Ventilation

I. Introduction

THE International Space Station (ISS) has evolved since beginning on orbit operations in 1998 to the present. The vehicle was constructed and maintained by the Space Shuttle, Russian Soyuz, and Progress vehicles through the retirement of the Shuttle fleet in July 2011. Since that time, there has been a transition in the vehicle configuration to accommodate NASA future planning to maintain ISS through cargo resupply and crew. Industry suppliers have successfully filled the Shuttle void by successfully providing cargo resupply to the station. HII-Transfer Vehicle (HTV), Dragon, and Cygnus resupply vehicles have delivered equipment and supplies to support continuing ISS operations. Crew vehicles are also progressing in development and will begin to deliver replacement crews to ISS in 2017.

Changes are necessary to the ISS interfaces to accommodate the various future visiting vehicle traffic. The ISS Program has initiated plans to reconfigure modules to support establishment of two cargo vehicle berthing ports and two crew vehicle docking ports. As a result, the program will relocate the Permananent Multi-Purpose Module (PMM) and Pressurized Mating Adapter #3 (PMA-3). See Figure 1. This will result in cargo vehicle berthing ports on the nadir side of Node 1 and Node 2. Pressurized Mating Adapter #2 (PMA-2) and PMA-3 will be located on the forward and zenith ports of Node 2, respectively, and will be used as crew vehicle docking ports. See Figure 1. New docking adapters will be installed on PMA-2 and PMA-3.

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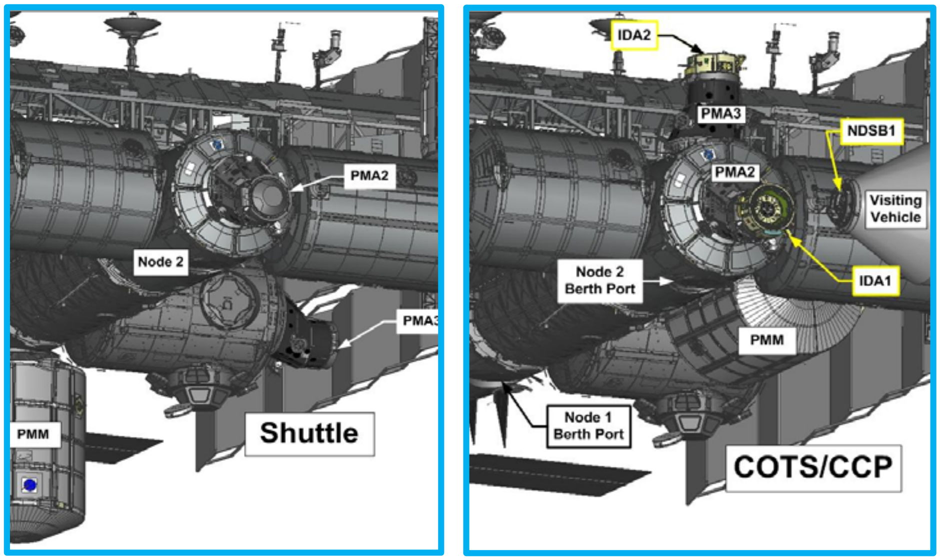

Figure 1 ISS Reconfiguration Layout

As a result of all these vehicle changes, internal systems require modification. This paper will focus on the changes to the IMV subsystem architecture required to support the new station configuration, including new hardware configurations, performance analyses, and acoustic noise analyses.

II. Inter-Module Ventilation Modifications in the Node 2 Module

A. Current Node 2 IMV Architecture

The current architecture of Node 2 supports a berthed cargo vehicle at the Nadir location, and previously supported a docked space shuttle vehicle at the forward facing PMA location. The current architecture of Node 2 is as shown in Figure 2. While there is an IMV fan at Node 2 Forward, it was originally installed to flow from the Space shuttle into Node 2. Since the Space Shuttle provided its own intermodule ventilation, this ventilation scheme was adequate to provide air exchange between the two vehicles. The Node 2 Zenith location has no capability to provide ventilation to a visiting vehicle. It is currently used as a backup berthing port, and has supported berthing of a HTV. As seen on the schematic, the other ports host permanent ISS modules. The US Lab is aft of Node 2, while Columbus is starboard and JEM is located at port.

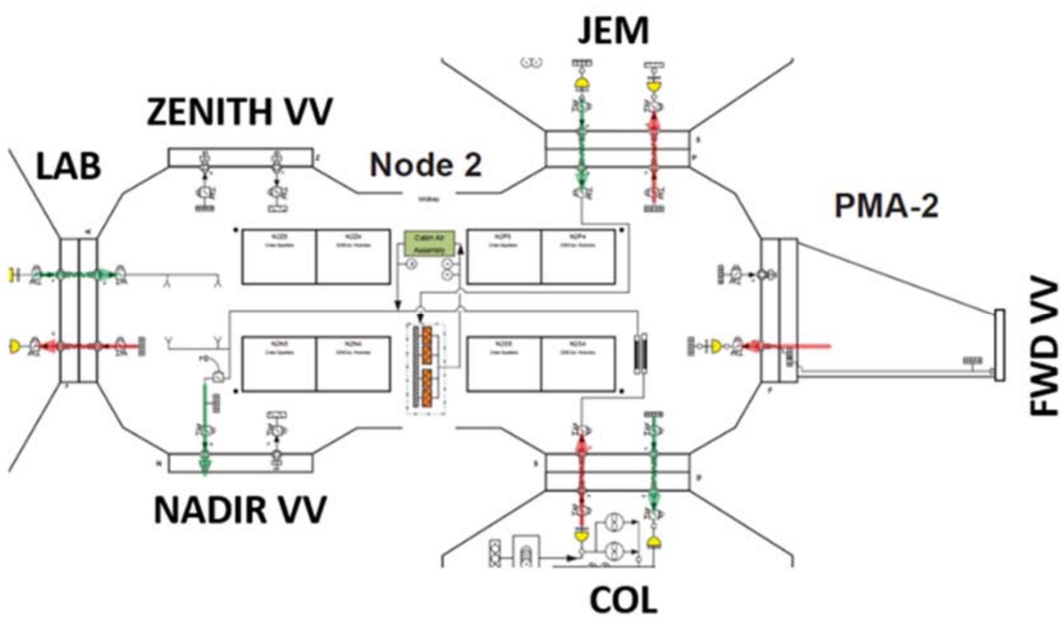

Figure 2 Node 2 Inter-Module Ventilation Schematic

B. Modified Node 2 Architecture

The modified Node 2 architecture is designed to provide ventilation to crewed visiting vehicles that will dock at Node 2 Forward and Node 2 Zenith. An IDA (International Docking Adapter) is being installed on PMA-2 at Node 2 Forward. To provide the additional docking port, PMA-3 is being relocated from Node 3 Port to Node 2 Zenith. A second IDA will be installed on PMA-3.

To facilitate providing intermodule and intramodule ventilation to visiting vehicles at the Nadir and Zenith locations, Node 2 requires significant modifications at those locations. Node 2 Zenith currently has no capability to provide ventilation. Both an additional IMV fan and associated ducting are required. While there is a fan located at the Forward location, the fan is oriented to pull air from the forward location. Assuming the fan does not stall, it could potentially provide adequate intermodule ventilation, as it is specified to flow 140cfm of air. However, since it is pulling, it will not provide adequate momentum at the inlet inside the visiting vehicle, meaning the air velocities inside the visiting vehicle would not be high enough to provide proper mixing. Hence the fan will have to be turned around to push air into the visiting vehicle. To 'push' intermodule ventilation air at both docking ports, the architecture of the ducting for both the docking locations had to be redesigned. Figure 3 shows the hardware and ducting modifications necessary to implement these changes.

To enable flow at the Zenith port, it was necessary to alter the supply and return sides of IMV. The fan that was previously used for return flow at Node 2 Forward, was reversed and is now used on the supply side at the Zenith/Forward location (i.e., blowing IMV into the vehicle docked at Node 2 Zenith location. Since the forward fan was used to feed zenith, another fan needed to be installed to supply ventilation at the Forward port. Space was limited, and it was determined that fans and silencers would only fit at Forward/Deck. To enable that, again, it was necessary to create a supply out of what was previously a return (once again, blowing IMV into the vehicle docked at the Node 2 Forward location).

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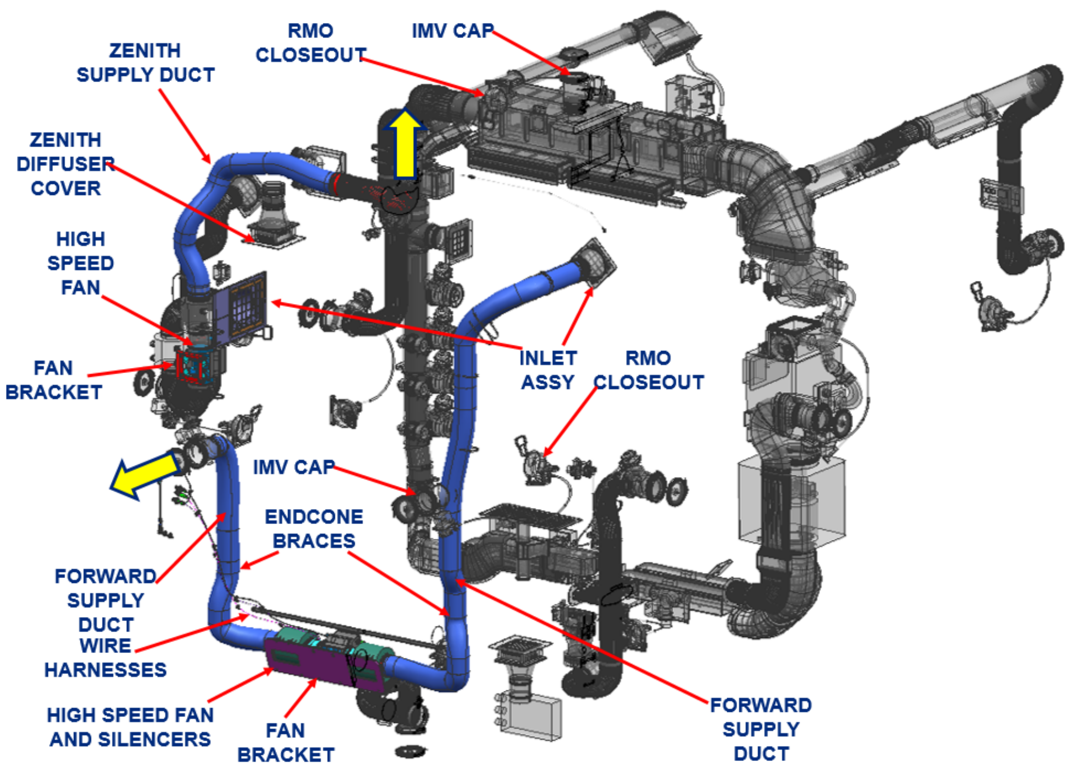

Figure 3 Node 2 Inter-Module Ventilation Hardware Modifications

C. Pressurized Mating Adapter Modifications

Once the IMV airflow exits Node 2, it travels through the Pressurized Mating Adapters (PMA) to the visiting vehicle at the Zenith or Forward location. In order to support the visiting vehicle interface location, a new duct was required in each of the PMAs. The ISS Program required an interface at the visiting vehicle that could be connected or disconnected quickly without the use of tools, so a new quick release coupling was developed to pass the airflow through to the visiting vehicle. In order to accommodate this new coupling, the ducting inside each PMA was replaced to provide clearance with the internal hatch. Figures 4 and 5 show the revised ducting and coupling design.

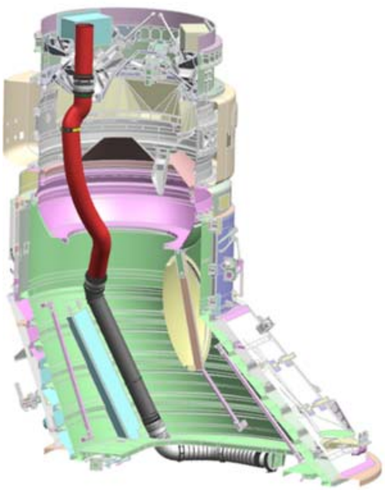

Figure 4 PMA IMV Hardware Modifications

Figure 5 ISS IMV Coupling

D. [1]Node 2 IMV Analysis

Given the new ducting configurations, it was necessary to analyze the delta pressure due to the new ducting configurations at the Node 2 forward and Zenith locations. The IMV fan is fixed speed, and is specified to produce 140cfm of flow at 1” H_2O. This could present a problem given the extra length of ducting necessary to provide flow to both ports. If the additional delta pressure from the ducting exceeds the fan specifications, it could result in a stall condition. In that condition the separation of the flow from the fan blades lowers the overall flow and produces loud noise.

An [1]analysis was performed using standard American Society of Heating and Air Conditioning Engineers (ASHRAE) methods to determine the pressure drop across the Node 2 ducting circuits at forward and zenith. This resulted in values of 345 Pa (1.39” H_2O) and 321.00 (1.29” H_2O) at 4.25m^3/m (150cfm), respectively. The dP due to the flow circuit exceeded the capability of the standard IMV fan, and meant that a fan that could provide higher flow and pressure head would be necessary.

To provide the higher flow/head, the standard IMV fan was modified to run at a higher speed. The modified fan has specifications that provide flow at 4.25m^3/m (150cfm) and 462.84 Pa (1.86” H2O).

Two main equations were used to calculate the pressure loss through the ducting. For geometries other than straight ducting, the following equation was used.

$$h = \frac{CoV^2}{2g}$$

Where,
h = Velocity Head Pressure
Co = Coefficient of loss for a particular geometry, based on empirical data in an ASHRAE table
V = Mean air speed
g = Gravitational constant used for unit conversion

The equation below was used for sections of straight ducting.

$$h = f\left(\frac{L}{Dh}\right)\left(\frac{V^2}{2g}\right)$$

Where:
h = Head Pressure
f = Friction coefficient, based on surface roughness
L = Length
Dh = Hydraulic Diameter
g = Gravitational constant used for unit conversion
V=Mean air speed

A 30% design margin was added to the resulting values. The results of these calculations provided a preliminary assessment of whether the design is compatible with the requirements. Further in the design process, testing was performed. Due to limitations of the available equipment, the highest achievable flow rate was 140 cfm. To correlate with test data, the values Co and f were increased by 30% for the Forward Supply Duct, the Silencers, and the IDA coupling and ducting. At Node 2 Zenith, the resulting pressure drop was calculated to be 1.29 in H2O at 150 cfm, including a 15% design margin. (Because the previous data had been correlated to test data, the design margin for both Forward and Zenith was reduced by half, from 30% to 15%.)

Table 1 shows the pressure loss due to each element in the Node 2 Forward IMV system. Table 2 shows the pressure loss due to each element in the Node 2 Zenith IMV system.

Table 1: Pressure Loss Due to Each Element in the Node 2 Forward IMV System

Component	**Delta P (Pa)**	**Delta P (inches H2O)**
Inlet screen	39.81	0.16
Reducer	2.49	0.01
Flex duct with two 90° and one 45° bend	12.44	0.05
Silencer	92.07	0.37
Silencer	92.07	0.37
Flex duct with two 90°	7.47	0.03
IMV Valve	19.91	0.08
PMA and IDA ducting	37.33	0.15
Total Delta P	301.10	1.21
With 15% design margin	**345.89**	**1.39**

Table 2: Pressure Loss Due to Each Element in the Node 2 Zenith IMV System

Component	**Delta P (Pa)**	**Delta P (inches H2O)**
Inlet screen	17.42	0.07
Reducer	2.49	0.01
Coupling and Bend	2.49	0.01
Silencer	92.08	0.37
U-Bend	7.47	0.03
Silencer	92.08	0.37
90° Bend	9.95	0.04
IMV Valve	19.91	0.08
PMA and IDA ducting	37.33	0.15
Total Delta P	278.71	1.12
With 15% design margin	**321.00**	**1.29**

III. Inter-Module Ventilation Modifications in the Node 3 Module

A. Current Node 3 IMV Architecture

As part of the creation of docking ports at Node 2, the entire USOS is being reconfigured. Node 1 Nadir is being reconfigured into a secondary berthing port, meaning that the PMM (Permanent Multipurpose Module) needs to be relocated. Node 3 Forward was chosen as the new location.

To accommodate the relocation, it was necessary to update intermodule and intramodule ventilation of Node 3.

Per design, and under the current configuration of the USOS, the PMM receives conditioned air via IMV. This is provided by the US Lab CCAA, by way of Node 1 IMV ducting.

The current configuration of the Node 3 Forward berthing port does not provide conditioned air for the PMM.

As shown in Figure 1, The current ducting configuration at Node 3 Forward has the port side as a supply, and the Stbd side as a return. The configuration runs counter to the configuration of PMM. PMM requires that the supply be on the Stbd side. The Starboard circuit also contains a fan that feeds the linear diffuser, which supplements intra-module ventilation. The IMV Feed-throughs are also capped, meaning valves will have to be installed to support ventilation.

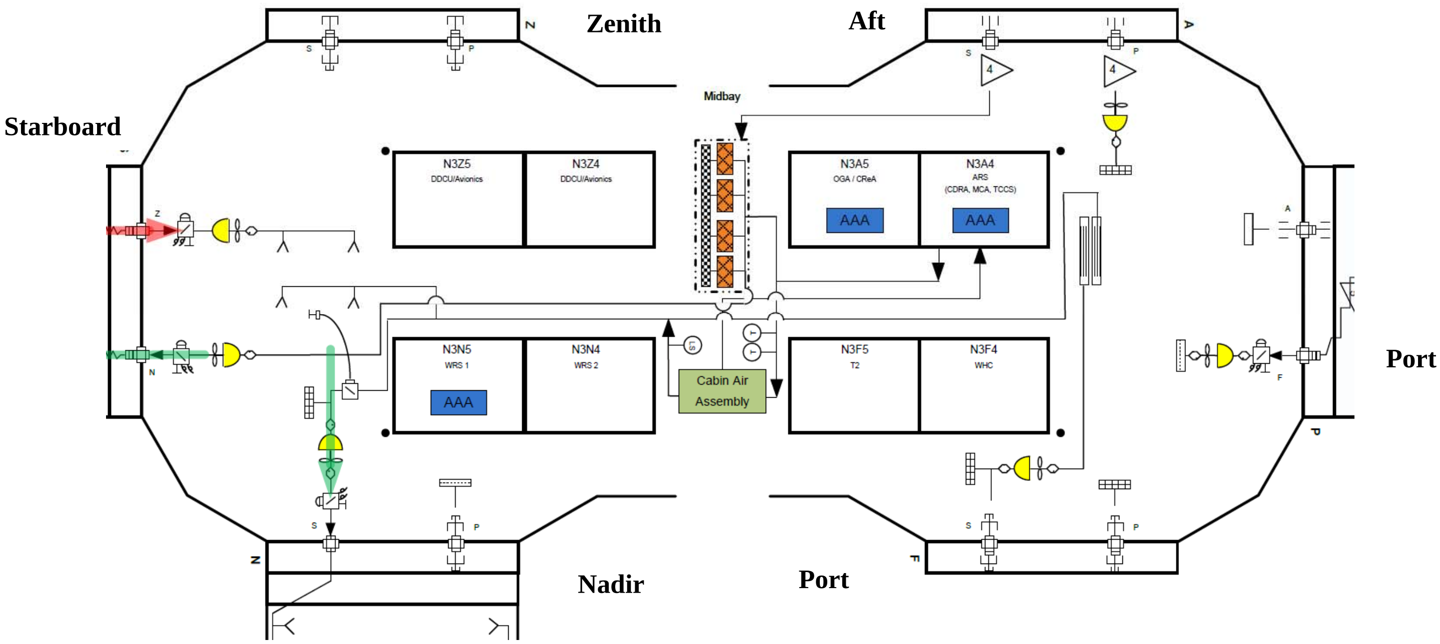

Figure 6 Node 3 Inter-Module Ventilation Schematic

B. Modifications

To support PMM, the current architecture of Node 3 Forward has to be completely re-engineered. The supply and return ventilation legs needed to be reversed. Conditioned air needs to be supplied to the PMM, while continuing to maintain the cool air supplied to Cupola and the Node 3 cabin.

These changes present challenges beyond simple architecture. The PMM module potentially adds 550W of heat to Node 3 per specification. This means that the Common Cabin Air Assembly in Node 3 will have to handle the additional loads. A THC/ARS analysis was to be performed to show that performance will be adequate, and that temperatures can be maintained. The analysis also shows if any operational considerations must be taken with regards to operation of the CCAA and the Cabin Fan driving ventilation.

To supply the conditioned air to PMM, the Fwd/stbd fan, and accompanying IMV circuit had to be removed. The ducting circuit to the Cupola was split, and used to provide conditioned air to both Cupola and PMM. A manual valve was added, to the circuit, so that a balance of flows could be maintained between Cupola and PMM, providing adequate ventilation and cooling to both modules. Ground development testing was performed using the Marshall

Space Flight Center (MSFC) Node Simulator to determine the best operational settings for the Variable Air Volume Damper Assembly (VAVDA) and new manual valve.

The deactivation and removal of the Node 3Fwd/Stbd IMV Fan means that half of the flow to the linear diffusers in the radial bay, integral to intramodule flow within Node 3, is lost. Analysis had to be performed to show that the added flow returning from the PMM hatch was adequate to replace flow lost at the linear diffuser.

To provide the ventilation at Fwd the Stbd leg of the IMV circuit was altered. The Fan and ducting feeding the linear diffuser has to be deactivated and removed. That leg is then tied into the CCAA. Figure 3 shows this architecture. Figure 8 shows a closeup of the changes made to Node 3 midbay ducting, to accommodate the ventilation modifications..

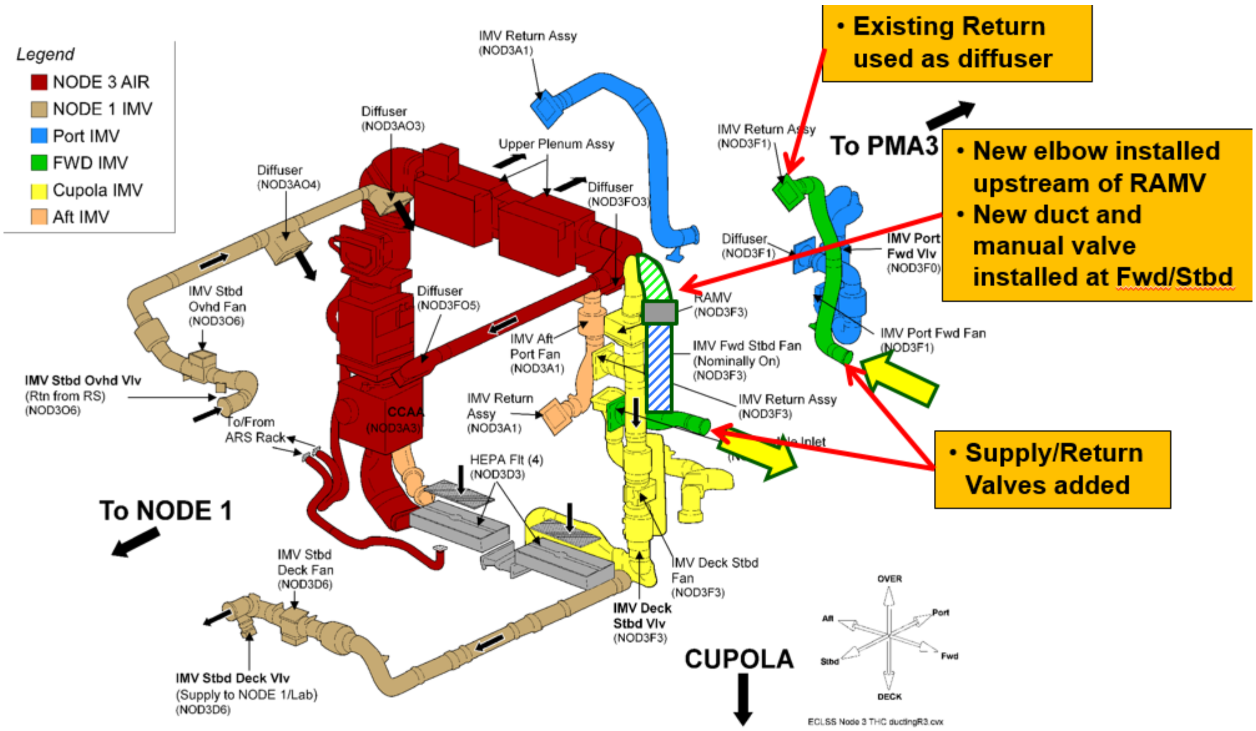

Figure 7 Schematic showing new IMV Circuit Feeding PMM at the Node 3 Forward Hatch

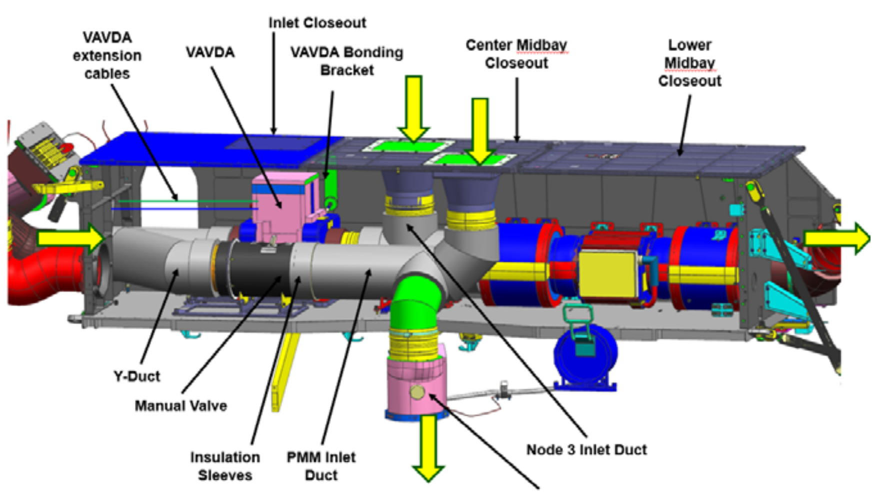

Figure 8Node 3 Forward Midbay Ducting Layout

C. [2]Node 3 THC and ARS Analysis

An analysis was conducted of the Node 3 THC and ARS performance, using the ISS SINDA/Fluint model. The Temperature and Humidity Requirements are as follows:

- Node 3 shall maintain a crew selectable cabin temperature between 18.3C (65F) and 26.7C (80F) under nominal heat loads (+/- 2ºF)
- PMM is treated as a heat load, and does not have temperature requirements
- Node 3 shall maintain Node 3 atmosphere relative humidity in the cabin aisle way within the range of 25 to 75 percent, excluding launch to activation.
- The dew point temperature within the Node 3 cabin aisleway shall be maintained within the range of 4.4C (40F) to 15.6C (60F), excluding launch to activation.

The variables explored within the analysis focused on the coolant temperature in Node 3 and the cabin fan speed. Below is the list of assumptions.

- Six crew members on board ISS
- PMM berthed at Node 3 Forward with CCAA and Cabin Air circulated throughout the volume with the PMM cabin fan operating at 4200 rpm
- Standard total airborn heat load in Node 3 is 2853 watts
  - PMM airborn heat lead is 650 watts for all cases
  - Node 3 heat load is 1623 watts
  - CCAA heat load is 450 watts for all fan speeds (conservative)
  - Crew metabolic rate includes two hours of exercise per day
- Hot case is 3293 watts (specification hot case)
- Node 3 CCAA fan speed is elevated at speeds varying from 4500 – 6050 rpm
- Node 3 low temperature thermal control system temperature is 4.4C-9.4C (40F – 49F)
- Node 3 cabin temperature is set at 18.3C (65F) – 22.2C (72F)
- Node 3 RAM-V valve is close and open to Cupola
- Manual Valve for conditioned air to PMM is open
- Lab low temperature thermal control system temperature is 9.4C (49F)
- Lab cabin temperature is set at 22.2C (72F)
- Node 2 low temperature thermal control system temperature is 11.1C (52F)
- Node 2 cabin temperature is set at 23.3C (74F)

Table 3 Shows the Case Matrix.

Table 3: Case Matrix

Case	Node 3 LTL	Node 3 Cabin Temperature Setpoint	Node 3 CCAA Fan Speed (RPM)	RAM-V to Cupola
1	9.4C (49F)	18.3C (65F)	4500	Closed
2	4.4C (40F)	18.3C (65F)	5270	Closed
3a	4.4C (40F)	18.3C (65F)	4800	Closed
3b	9.4C (49F)	18.3C (65F)	4800	Closed

Case 1 shows the pre-modification conditions. Case 2 is a hot case, max loads, used for verification of the system performance. Case 3a & 3b were used to show recommended operations. Results for the recommended option is shown in Figure 9.

While Case 2 does meet all requirements, it also means running the CCAA Fan at the highest speed. The high speed would exceed the acoustic waiver that is presently in place, and create a noise hazard. Case 3a & 3b show a compromise that will meet the needs of the crew, and maintain an acoustic atmosphere that stays within the requirements. Temperature can only be maintained as low as 20.1C (68.2F), however history shows that the crew generally keeps the temperature inside the USOS at or above 22.2C (72F). With the Low Temperature Loop LTL configured as high as 9.4C (49F), which is the highest allowed when running the Carbon Dioxide Removal Assembly, the lowest selectable cabin temperature is not expected to exceed 21.7C (71F).

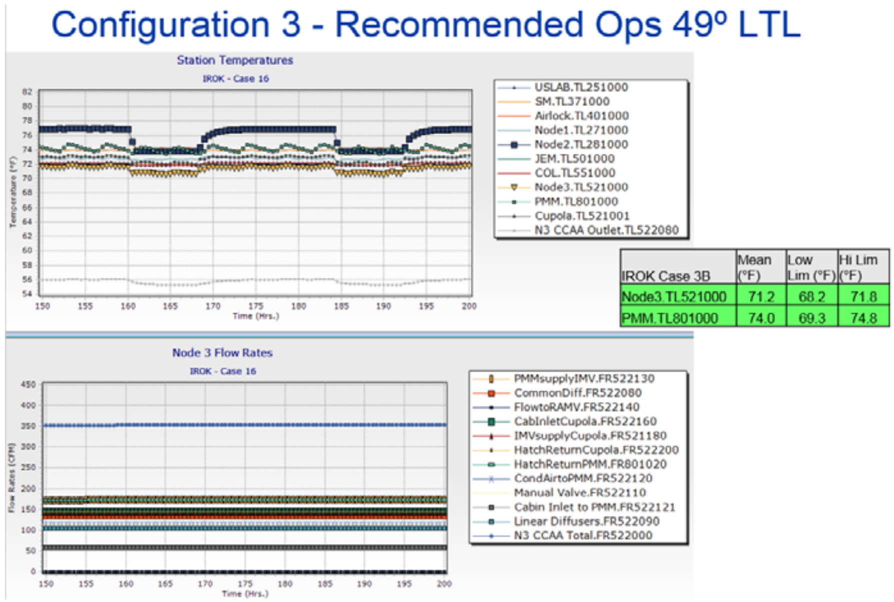

Figure 9 Configuration 3 Results; [3]Intramodule Ventilation Analysis

D. [3]Air Velocities Analysis

A [3]Computational Fluid Dynamics Analysis was performed, to show that the air velocities could be maintained in the Node 3 cabin despite half of the flow being lost at the linear diffuser. The requirements state that an effective atmosphere velocity in the cabin aisleway must be maintained between 4.6 and 12.2 meters per minute (15 and 40 feet per minute). Two-thirds of the flow must be maintained in this range, with no more than 5 percent of the flow being below 2.1 meters per minute (7 feet per minute), and no more than 1 percent of the flow being above 61.0 meters per minute (200 feet per minute).

Figure 10 shows a pictorial view of the results of the altered radial bay airflows in Node 3. Flows from the overhead diffusers are followed, and analysis shows that the required range of velocities is maintained.

Table 4 shows the overall air velocity distrubutions both pre-, and post-modification. The results show that the loss of half of the flow from the linear diffuser was supplemented by the return flow coming from the hatchway of the PMM. The new ventilation scheme meets requirments, and actually shows an improvement in the 4.6 - 12.2 meters per minute (15-40 feet per minute) range (i.e., by reducing the regions of air velocities above 40 fpm).

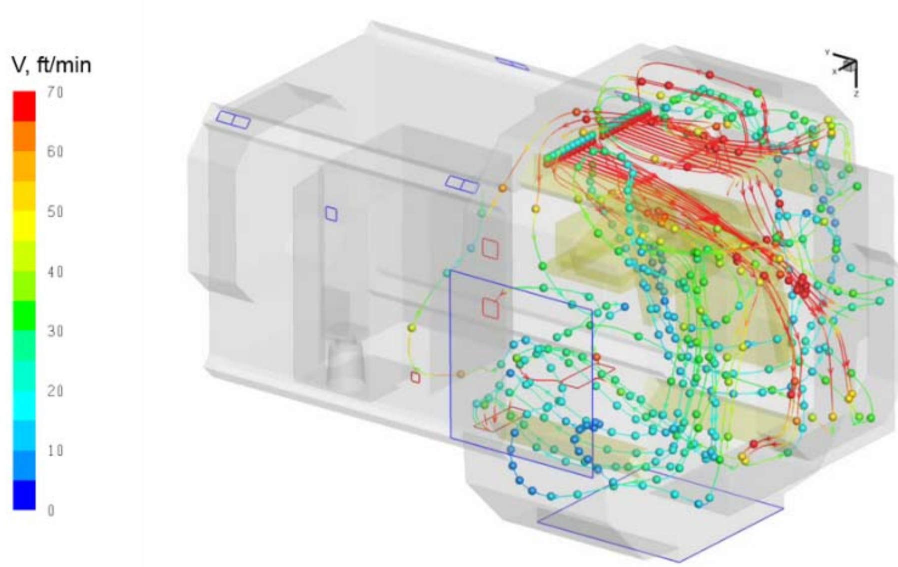

Figure 10 Predicted Intramodule Airflow in Node 3 Radial Bay Post-Modification

Table 4 Cabin Air Velocity Distributions in Node 3 Radial Bay

Table for Distribution of time-averaged velocity magnitude

	Velocity Magnitude (ft/min) (1)				
	Below 7	7 – 15	15 – 40	40 – 200	Above 200
Node 3 Case1 (Baseline)	**1.6%**	**8.8%**	**67.9%**	**21.1%**	**0.6%**
Node 3 Case2 (Mod)	**3.8%**	**13.1%**	**70.0%**	**13.0%**	**0.1%**

1. Velocity magnitude distribution of fluid zones 6 inches away from all the walls.

2. Velocity magnitude, V_a, estimated as $V_a = \sqrt{V_m^2 + \frac{5}{3}k}$, where V_m is the mean velocity magnitude and k is the turbulent kinetic energy.

IV. Conclusion

The proposed changes to the ISS Intermodule Ventilation system architecture will support all current vehicle operations as well as future activities including visiting cargo and crew vehicle missions. The IMV changes are currently underway, and are expected to be completed in advance of the first planned docked visiting vehicle mission.

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