

# Assessment of the Impacts of ACLS on the ISS Life Support System using Dynamic Simulations in V-HAB

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The Advanced Closed Loop System (ACLS) is currently under development by Airbus Defense and Space and is slated for launch to the International Space Station (ISS) in 2017. The addition of new hardware into an already complex system such as the ISS life support system (LSS) always poses operational risks. It is therefore important to understand the impacts ACLS will have on the existing systems to ensure smooth operations for the ISS. This analysis can be done by using dynamic computer simulations and one possible tool for such a simulation is Virtual Habitat (V-HAB). Based on Matlab®, V-HAB has been under development at the Institute of Astronautics of the Technical University Munich (TUM) since 2006 and in the past has been successfully used to simulate the ISS life support systems. The existing V-HAB ISS simulation model treated the interior volume of the space station as one large ideally-stirred container. This model was improved to allow the calculation of the atmospheric composition inside the individual modules of the ISS by splitting it into ten distinct volumes. The virtual volumes are connected by a simulation of the inter-module ventilation flows. This allows for a combined simulation of the LSS hardware and the atmospheric composition aboard the ISS. A dynamic model of ACLS is added to the ISS simulation and different operating modes for both ACLS and the existing ISS life support systems are studied to determine the impacts of ACLS on the rest of the system. The results suggest that the US, Russian and ACLS CO<sub>2</sub> systems can operate at the same time without impeding each other. Furthermore, based on the results of this analysis, the US and ACLS Sabatier systems can be operated in parallel as well to achieve the highest possible CO<sub>2</sub> recycling together with a low CO<sub>2</sub> concentration.

## Nomenclature

<i>ACLS</i>	= Advanced Closed Loop System	<i>LSS</i>	= Life Support System
<i>CCAA</i>	= Common Cabin Air Assembly	<i>OGA</i>	= Oxygen Generation Assembly
<i>CDRA</i>	= Carbon Dioxide Removal Assembly	<i>PMM</i>	= Permanent Multipurpose Module
<i>CFD</i>	= Computational Fluid Dynamics	<i>Rec.</i>	= Recovery
<i>CHX</i>	= Condensing Heat Exchanger	<i>SCRA</i>	= Sabatier CO <sub>2</sub> Reprocessing Assembly
<i>ESA</i>	= European Space Agency	<i>SM</i>	= Service Module
<i>FGB</i>	= Functional Cargo Block	<i>V-HAB</i>	= Virtual Habitat
<i>HX</i>	= Heat Exchanger		
<i>IMV</i>	= Inter-Modular-Ventilation		
<i>ISS</i>	= International Space Station		
<i>JEM</i>	= Japanese Experiment Module		

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## I. Introduction

IN order for humans to survive in space they require reliable life support systems (LSS) which in general are complex systems with many dynamic effects that influence each other. Understanding and analyzing such systems is no simple task and since they are critical to the survival of humans onboard the space craft it is necessary to identify possible problems ahead of time. For that reason, computer simulations are often used to simulate LSS. One simulation tool for dynamic simulations is Virtual Habitat (V-HAB). The V-HAB Project was started in 2006 at the Institute of Astronautics of the Technical University Munich<sup>1,2</sup>. It aims to provide a dynamic and modular framework for various LSS simulations. The goal of this paper is to use V-HAB for an independent analysis of the possible impacts the Advanced Closed Loop System (ACLS) will have on the ISS atmosphere. ACLS is currently under development by Airbus Defense and Space in cooperation with the European Space Agency (ESA) and is slated for launch in 2017<sup>3</sup>. The first step for this analysis was to create a dynamic model of ACLS that correctly reflects its impact on the atmosphere. The presented work was performed without any affiliation to Airbus Defense and Space or ESA and all data used for the model is publicly available. Aside from a model for ACLS it was also necessary to model the International Space Station (ISS) LSS and atmosphere, which had already been done by previous work that modeled and validated a simulation of the ISS in V-HAB<sup>4</sup>. This simulation was migrated from the V-HAB 1.0 structure to the new V-HAB 2.0 structure that now allows dynamic varying time steps instead of a constant 60s time step<sup>5,6</sup>. The developed model was then improved and updated in Reference 7. While the improvements entailed changes to the ISS LSS subsystems like the Carbon Dioxide Removal Assembly (CDRA) or the Common Cabin Air Assembly (CCAA) these changes will not be discussed in this paper as the focus of the paper will be the analysis of the impacts ACLS has on the ISS atmosphere. Therefore, the only change to the ISS model that will be discussed in this paper is the migration from a model with one discrete volume to a model with ten discrete volumes.

While other models of the ISS atmosphere with a more precise representation of the atmosphere exist<sup>8</sup> these are currently separated from the simulation of the LSS hardware. However, the atmosphere has a direct influence on e.g. the adsorption of CO<sub>2</sub> for zeolite or the performance of a condensing heat exchanger. If the simulation of the LSS hardware assumes one ideally stirred volume for the ISS atmosphere the impact of local differences in the atmospheric composition will be completely neglected. On the other hand, a detailed computational fluid dynamic (CFD) model for the atmosphere requires too much computation time for a system level LSS simulation that has to simulate timeframes from days to months. However, since the atmospheric composition influences the LSS hardware and the LSS hardware in turn influences the atmospheric composition it is preferable to model both effects within one simulation to allow a direct coupling of these effects.

Therefore, the model presented in this paper splits the ISS into ten discrete volumes and uses volumetric flow rate calculations for the Inter-Modular-Ventilation (IMV) flows. This enables the simulation to account for changes in the atmospheric composition as each module of the ISS has an individual atmospheric composition, while not requiring a full CFD simulation of the ISS atmosphere, thus achieving sufficiently low simulation times for a system level model. This improved modelling approach is then used to analyze the impacts ACLS will have on the ISS atmosphere and the other LSS onboard the ISS.

## II. ACLS Model

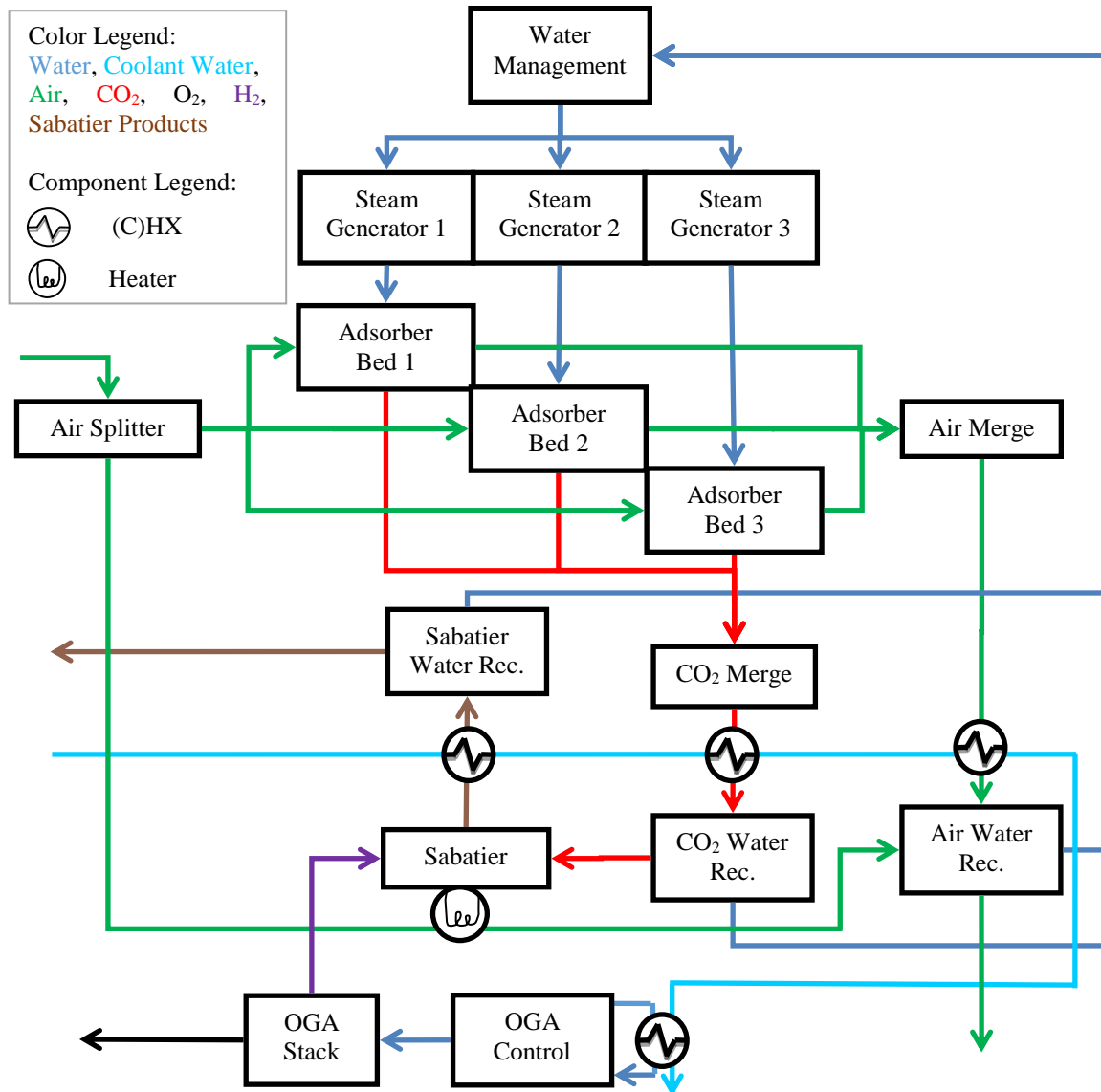
ACLS is a LSS that combines the air revitalizing functions of CO<sub>2</sub> removal, CO<sub>2</sub> recycling and O<sub>2</sub> generation. For CO<sub>2</sub> removal three adsorber beds with thermal amine are used. Instead of a pressure swing for desorption these beds use super-heated steam for their desorption process<sup>9</sup> and according to the ACLS mass balance<sup>3</sup> some of the water used during desorption is released to the cabin as humidity. Therefore, ACLS impacts the atmosphere not only in the CO<sub>2</sub> and O<sub>2</sub> level but also affects the relative humidity. The model for ACLS has to correctly reflect these impacts. First the modelling approach used to achieve this is explained and then the model is validated to show that the created model fits known data of ACLS.

### A. Modelling Approach

Overall the focus of the ACLS model was to represent the impacts ACLS will have on the atmosphere as closely as possible, but not to model ACLS itself in great detail since the amount of data available for that goal was not sufficient. The most basic approach to achieve this would be to assume constant flow rates at the interfaces of ACLS that would neglect all dynamic behavior of ACLS. Therefore, ACLS was modeled to a degree that allowed a dynamic representation of its impacts. That required the simulation of internal dynamic behavior for ACLS and resulted in a dynamic model of ACLS. Since the presented work was performed based only on publicly available data it was necessary to fill missing information with plausible assumptions. For example, the adsorbent mass in

each absorber bed was unknown and had to be estimated based on the isotherm of the amine used in ACLS, the cycle time and the CO<sub>2</sub> removal capability of ACLS.

The following Figure 1 shows a functional block diagram of the model that will be used to explain it in a bit more detail.



**Figure 1. Functional Block Diagram of the ACLS Model (based on Reference 10).**

The information on the individual parts of ACLS was limited, but it was still possible to implement a model that represents all the components individually. Aside from the fact that this allows a more dynamic simulation of ACLS it also allows the model to be easily improved as additional information about individual subsystems becomes available. In addition to the impacts on humidity, CO<sub>2</sub> and O<sub>2</sub> the model also calculates the temperature increase of the coolant water from the three Condensing Heat Exchangers (CHX) and the sensible, non-condensing heat exchanger (HX) used to control the temperature of Oxygen Generation Assembly (OGA). The excess heat produced in the Sabatier reactor that is not required to maintain the reaction temperature is assumed to transfer completely into the coolant air flow passing by the Sabatier reactor, which together with the CHX models yields a good estimate for the outlet temperature of the air flow. The model also includes additional features of ACLS that are not shown in Figure 1 such as the air save mode that reroutes air at the beginning of the desorption process back to the air splitter<sup>3</sup>.

Again further more in depth explanation about the individual subsystem can be found in Reference 7.

## B. Validation

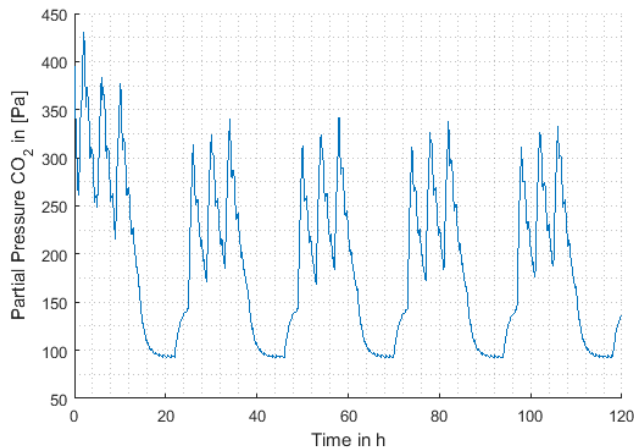
ACLS has three primary impacts on the atmosphere that are the main topics of the analysis. Therefore, the focus of the validation was to show that these three main concerns are represented correctly by the model. For that purpose, a simulation of a small space craft with a crew of three humans and ACLS as sole LSS was created. Since ACLS is the only system affecting the atmosphere aside from the crew all impacts on the atmosphere had to originate from ACLS which made validation easier.

The first value that is discussed here is the humidity release to the cabin, or more accurately the overall water mass balance. Since the simulation is dynamic the mass balance changes slightly for different conditions in the cabin atmosphere. Therefore, the simulation results shown in Table 1 are averaged over 5 days to minimize these effects and get a close representation of the general water mass balance for the ACLS model. This mass balance was then compared to the water mass balance released by Airbus<sup>3</sup>.

**Table 1. ACLS Water Mass Balance Validation.**

	Simulation (5 Day average)	Mass Balance <sup>3</sup>	Percent Deviation
Humidity Release	4.77 kg/day	4.9 kg/day	3.99%
Water Recovered from Air	2.45 kg/day	2.4 kg/day	2.14%
Water Recovered from Steam desorbed CO <sub>2</sub> Stream	0.86 kg/day	1 kg/day	14.37%
Water Recovered from Sabatier	1.30 kg/day	1.2 kg/day	8.54%

The humidity release value from the table represents the amount of water that is released to the cabin while the water recovered from air is the amount of water that is removed from the outlet air stream before it is released to the cabin. Overall this means that about 7.3 kg of the water used during the steam desorption ends up in the air. The simulation showed good correspondence for the humidity release and the water recovery from air within a margin of error of less than 4%. The value for the water recovered from the Sabatier is off by about 8.5% but this should be acceptable as it is a value that only affects ACLS internally. The only value that showed a deviation of more than 10% was the water recovery from the carbon dioxide stream. However, that can be explained if the water mass balance data for ACLS is examined a little closer. In total the water mass balance states that 8.3 kg of water are used in ACLS each day for steam desorption<sup>3</sup>. If the values for humidity release and water recovery from air are subtracted from this value, the 1 kg value for the water recovery from CO<sub>2</sub> can be calculated. But that assumes a 100% efficient CHX (Condensing Heat Exchanger) and also neglects water losses that are up to 90 g/day<sup>3</sup>. The simulation did account for these effects and the vented mass of water was about 65 g/day. If these effects are taken into account a lower value for the water recovery from CO<sub>2</sub> seems plausible.



**Figure 2. ACLS Partial Pressure CO<sub>2</sub> Validation.**

Aside from the humidity release the removal of CO<sub>2</sub> from the atmosphere is another one of the major tasks. The ACLS design requirement<sup>11</sup> states that ACLS has to remove the CO<sub>2</sub> produced by three crew members, currently estimated at 3.12 kg/day<sup>12</sup>, a partial pressure of 300 Pa for CO<sub>2</sub>. However, the actual capability of ACLS was tested to be 4.1 kg/day of CO<sub>2</sub> removal at 300 Pa partial pressure<sup>3</sup>. Unfortunately, the removal capability is only given for one specific partial pressure of CO<sub>2</sub>. In a dynamic simulation the partial pressure of CO<sub>2</sub> in the atmosphere is not constant and it had to be validated that the ACLS model is able to remove the metabolic load of three humans with a daily schedule of exercise, nominal and sleep activities. The resulting CO<sub>2</sub> partial pressure plot for the that simulation is shown in Figure 2.

The plot shows three distinct spikes in the CO<sub>2</sub> level per day. These are a result of the one-hour exercise period of one of the crew members respectively. The following dent in the partial pressure can be explained because of the 8-hour sleep period during which all three crew members are asleep. Overall the plot shows that ACLS is able to keep the partial pressure even lower than 300 Pa for most times and it validates that the CO<sub>2</sub> removal of the model scales with the partial pressure. The partial pressure remains below 300 Pa because of the increased performance of ACLS as shown in tests<sup>3</sup>. The oxygen release is independent from the atmospheric composition and therefore a detailed validation of the Oxygen Generation Assembly (OGA) is not shown here.

### III. ISS Model

Previously the ISS model in V-HAB used a single ideally stirred volume to represent the ISS atmosphere. Efforts had already been made to achieve a better representation by using at least three volumes instead of just one but because of solver issues that approach had to be dropped at first.<sup>5</sup> The improvements made to V-HAB in the meantime now allowed a representation of the ISS atmosphere with an arbitrary number of volumes. Because of performance considerations the number of volumes used to describe it was limited to ten for this simulation. In the following section the detailed reasoning for that value and the basic modelling approach for the ISS will be explained, followed by a section covering the validation of the ISS simulation.

#### C. Modelling Approach

As stated in the introduction this paper will not discuss the subsystem models for the ISS LSS like CDRA, SCRA and CCAA in detail and will instead focus on the model of the station atmosphere. Detailed information about the subsystem models can be found in the reference 7.

##### 1. Atmosphere Model

The ISS in total has a volume of about 800 m<sup>3</sup> of free air<sup>11</sup> but the individual modules have a much smaller volume (e.g. Node 3 has a volume of free air of ~62 m<sup>3</sup>)<sup>9</sup>. Therefore, if the ISS atmosphere is modelled as one large ideally stirred volume the impact of local changes in the atmosphere will be completely neglected and the whole system will react slower to changes. For example, if a crew member starts exercising and produces more carbon dioxide and humidity it makes a sizeable difference if that change instantly affects the whole 800 m<sup>3</sup> or if it only affects 62 m<sup>3</sup> and then has to spread to the remaining volume. Therefore, the ISS atmosphere model was split up into ten discrete volumes that are each assumed to be ideally stirred. The configuration of the volumes and the connecting IMV flows are shown in Figure 3 below.

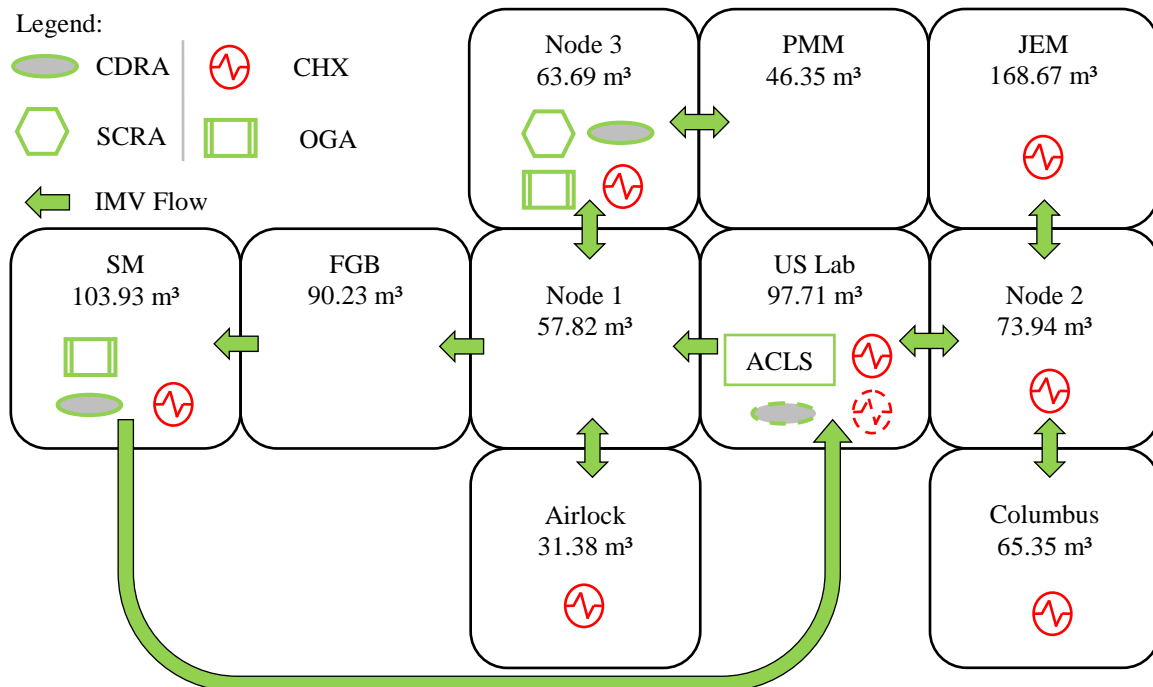


Figure 3. ISS Configuration for the Simulation.

The smaller modules not shown in Figure 3 are added to the volume of the larger volumes to achieve a realistic representation. For example, the volume of the Service Module (SM) node is calculated from the Service Module volume of 90.53 m<sup>3</sup> and the Mini Research Module volume of 12.49 m<sup>3</sup> that is attached to it. All volumes in the figure are calculated from the values given in Reference 11. As mentioned before it would be possible to use a larger number of volumes for the model but it is necessary to weigh the gained quality improvement with the loss in performance. The current configuration of the volumes was chosen based on the location of the LSS hardware. Each module that contains LSS hardware was kept as one individual module to keep the volume that is *directly* influenced by each piece of hardware as realistic as possible.

The LSS hardware that Figure 3 shows in the Service Module are obviously not actually a CDRA and OGA. But since little information on the Russian LSS was available slightly adapted models of CDRA and OGA were used to achieve a realistic representation for these systems. Therefore, the sketch does not differentiate between the Russian and the US Systems. The CDRA and the CHX in the US Lab with the dashed outline are normally not active. They were included in the simulation but the systems were turned off and did not affect the atmosphere.

The configuration for the IMV flows was taken from Reference 8 while the ISS configuration was updated to the current configuration. Each IMV flow, symbolized by a green arrow in Figure 3, represents a volumetric flow rate of 140 cfm. This volumetric flow rate was assumed to be constant and the only connection between the different modules. Of course in reality there are other forces providing a mixing effect like diffusion or pressure differences between the modules. These forces were neglected which means that the overall mixing effect between the modules was underestimated by the simulation. On the other hand, the mixing within each module was overestimated because it was assumed to be ideally stirred. Therefore, including all mixing effects between the modules would have resulted in an overestimation of the overall mixing. One might think that by using a constant flow rate between the modules pressure differentials between them will increase indefinitely over the simulation time. But because a volumetric flow rate was used this does not occur. While the volumetric flow rate was constant the mass flow resulting from it changed for each time step because the density in each module changed. The mass flow was calculated by multiplying the volumetric flow rate with the origin module density. In a module with a higher pressure the density was higher resulting in a higher mass flow going out of the module while the ingoing mass flows were constant (assuming that the pressure in the other modules was constant). This resulted in a slower pressure equalization than a more precise CFD calculation but the highest pressure difference between two modules that occurred in the simulation was ~100 Pa which suggests that this simplification was valid.

## 2. Human Model

The human model used to inject the metabolic loads of the crew is also important to the simulation. Since the atmosphere model was changed from one large volume to several smaller ones it became necessary to implement a human model that allowed the crew to freely move through the ISS in the simulation. That means the human model not only required information about the current activity of the crew member, like sleeping or exercising, but also on the current location. The human model used for this simulation was based on the values given in Reference 12 for different states of the humans. It can therefore reflect the amount of humidity and carbon dioxide produced and the amount of oxygen consumed by humans for different metabolic loads. The simulation assumed a crew of six humans that was spread out through the ISS during the day with one crew member each being in the Service Module, Functional Cargo Block (FGB), Node 3, US Lab, Columbus and Japanese Experiment Module (JEM). Additionally, each crew member had one hour of exercise scheduled per day and moved to Node 3 to perform this task. It was assumed that during each exercise period, two crew members exercised at the same time. Finally, for the night the simulation assumed that four crew members sleep in Node 2 and the remaining two in the Service Module.

**Table 2. Qualitative Crew Timeline.**

Crew 1	US Lab	Node 3	US Lab	Node 2	US Lab
Crew 2	Node 3	Node 3	Node 3	Node 2	Node 3
Crew 3	Columbus	Node 3	Columbus	Node 2	Columbus
Crew 4	FGB	Node 3	FGB	SM	FGB
Crew 5	JEM	Node 3	JEM	Node 2	JEM
Crew 6	SM	Node 3	SM	SM	SM
Legend	green Background is nominal metabolic load		red is exercise	grey is sleep	

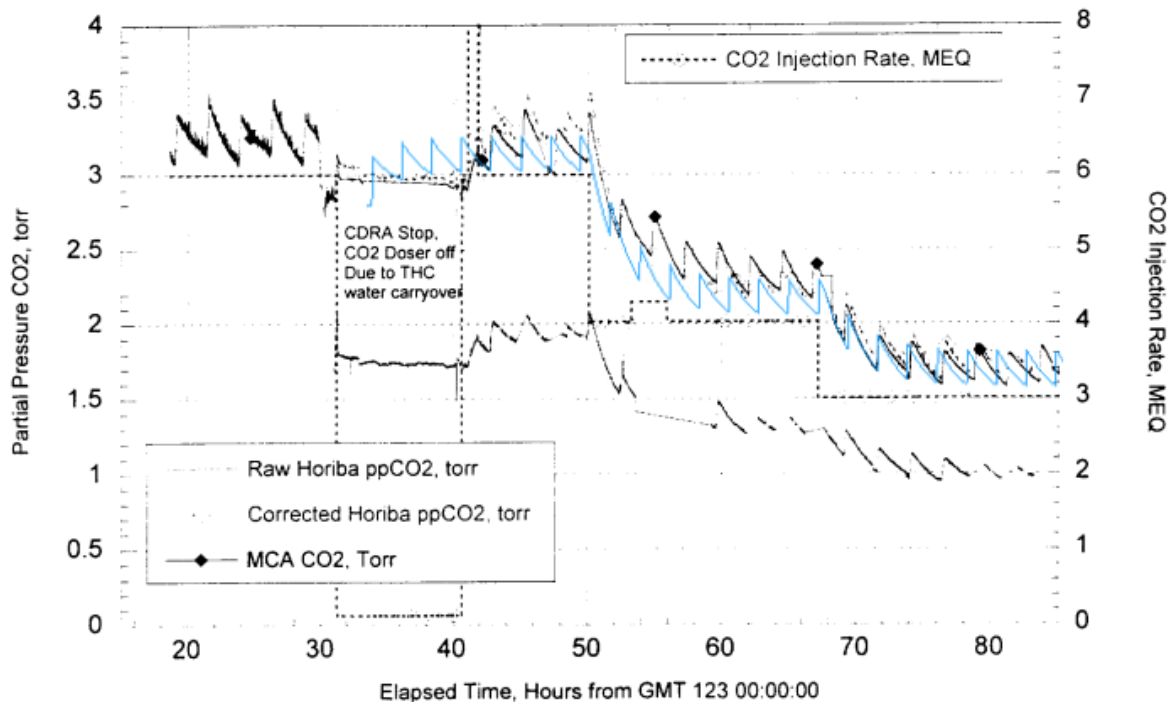


The qualitative crew time line shown in Table 2 shows the basic crew schedule used for this simulation for each day. The simulation is assumed to start at eight o'clock on the first day and therefore zero hours of simulation time are identical to eight o'clock in the morning. The text in each block of the table represents the location of the crew member while the color shows the current metabolic load as explained in the legend. The representation is only qualitative since individual size of the blocks is not in a correct proportion regarding the actual time of the activities.

So far the model only considered pressure and composition of the atmosphere not the thermal aspect of it. Obviously the temperature has a large impact on a variety of values like the humidity or the performance of the CHX. However, for a correct simulation of the temperature it would have been necessary to model not only the humans and the LSS but also all payloads that release heat. This would have exceeded the scope of this analysis and therefore the temperature onboard the ISS was assumed to remain constant at 22.2°C. The chosen temperature was based on the history for crew preferences according to Reference 13.

#### D. Validation

Since a previous paper already discussed the validation of the current ISS LSS within V-HAB<sup>4</sup> this paper will only give a very brief overview of the performed tasks. To validate the simulation, the subsystems were first tested individually to ensure that each of the LSS components work as intended. As an example of this validation the overlay of CDRA test data and simulation data is shown in Figure 4 below.



**Figure 4. Validation for CDRA model (blue line) with test data (black line) from Reference 14.**

Figure 4 shows the correspondence of the simulation data and the test data is good for all three CO<sub>2</sub> levels. Similar validations were made for the other subsystems of the ISS except Vozdukh, since no test data for Vozdukh could be obtained. As mentioned before, this paper will not discuss all LSS subsystems in detail, but additional information about it can be found in Reference 7. Therefore, it is assumed that the LSS models of the ISS worked as intended. That only leaves the validation of the atmosphere model which represents the ISS atmosphere composition of pressure, temperature and the individual partial pressure for the modules. The results of the simulations were validated against the same data that was used in Reference 4 but that did not allow a detailed validation of the atmosphere model since the telemetry data was not provided for all modules represented in the model. However the levels for CO<sub>2</sub>, H<sub>2</sub>O and O<sub>2</sub> remained within the respective limits set for the ISS<sup>12</sup> and overall resulted in a plausible representation of the ISS atmosphere.

#### IV. Simulation Results

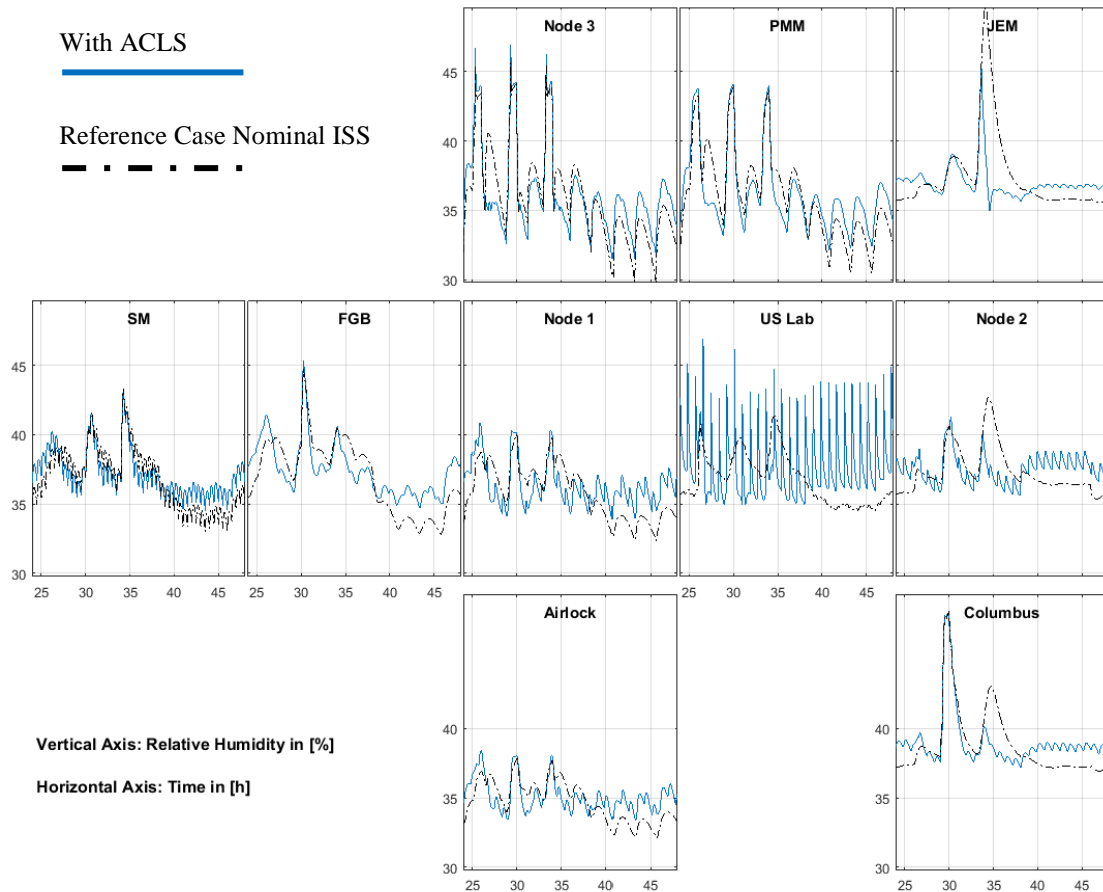
This paper will discuss the results of two simulated cases. The first case assumed that the current ISS LSS is continuing to operate nominally and ACLS is activated additionally. The second case assumed that the US systems for CO<sub>2</sub> removal and recycling (CDRA and SCRA) as well as the systems for O<sub>2</sub> production (OGA) are offline and ACLS has to replace these functions. Since all O<sub>2</sub> generating systems aboard the ISS use electrolyzers the oxygen production is independent from the atmosphere and therefore no results will be shown for the oxygen level in the atmosphere. However, the simulation did contain models of the Russian electron VM, the US Oxygen Generation Assembly and the ACLS Oxygen Generation Assembly and their effects on the atmosphere were modeled. To make it easier to identify the impact of ACLS on the atmosphere the plots will show the results for the simulation of the current ISS LSS configuration as dashed black lines and the results for the simulated case as blue line. The results for each of the simulated modules will be shown in individual subplots that each have the same range for the x- and y-axis and have a title reflecting the name of the ISS module that is represented. The positioning for the subplots reflects the actual position of the modules of the ISS as shown in Figure 3.

##### A. Current ISS LSS Configuration with ACLS

The configuration used for the LSS in this case is shown in Table 3. Any LSS that is not mentioned is considered to be active in all cases.

**Table 3. LSS Hardware Status for the First Case**

Node 3				US Lab			
CDRA	CCAA	SCRA	OGA	CDRA	CCAA1	CCAA2	ACLS
ON	ON	ON	ON	OFF	ON	OFF	ON

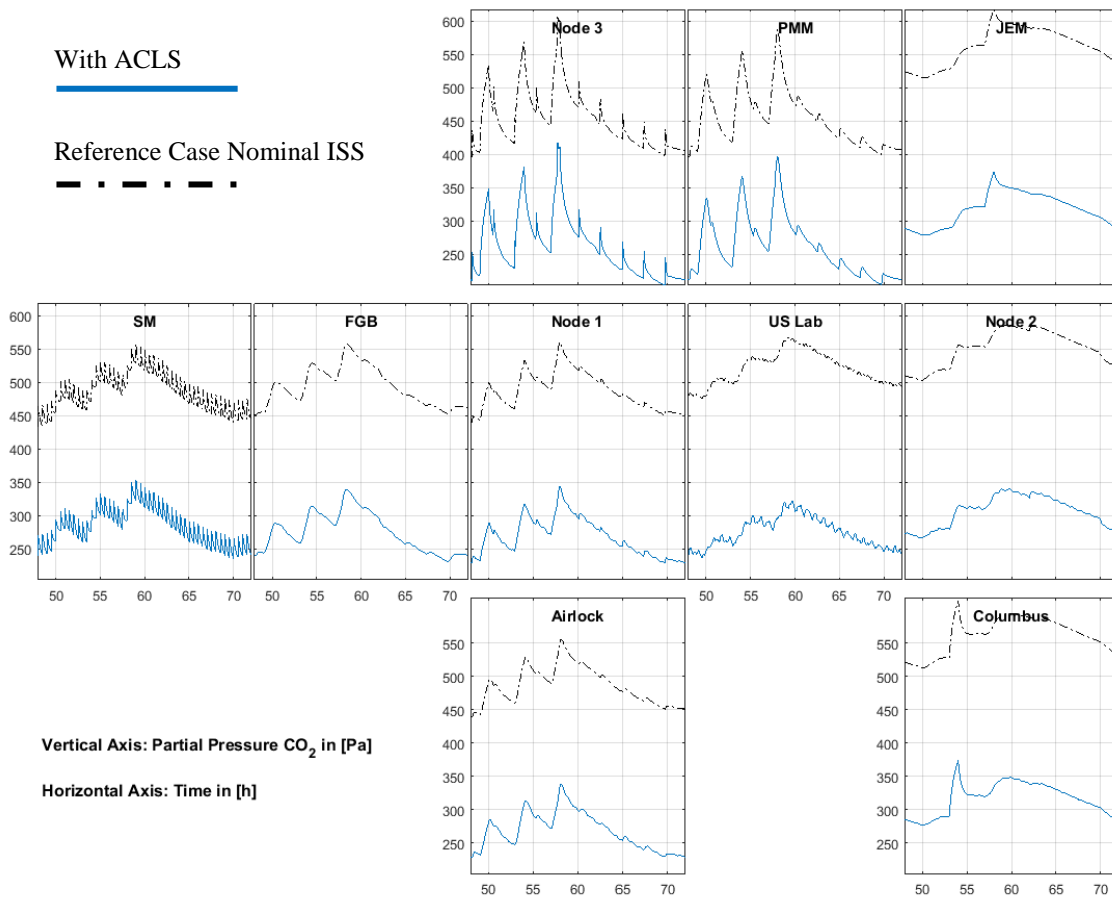


**Figure 5. ISS Relative Humidity Simulation Results for the current ISS LSS configuration with ACLS.**



The results shown in Figure 5 are for the second day of the simulation from hour 24 to 48. The second day was chosen because the results for the following days are nearly the same with each day repeating the same cycle as the one seen on day two. The three spikes occurring in Node 3 can be explained with the crew activity schedule. Each spike represents two crew members exercising in Node 3. The spikes in Columbus, Node 2 and JEM occurred because the crew member who normally work there just finished exercising and came back. Directly after exercising the humidity release of the crew member was still higher than normally thus increasing the humidity in the module for some time after the return. Aside from the crew effects a slow gradual spread of the humidity spike from Node 3 to the other modules could be observed. In the US Lab small spikes occurred in regular time intervals because of the humidity release from ACLS. For the real system these spikes would not occur since the release of humidity from the absorber beds is a slow process. However, in the simulation it was assumed that the complete humidity stored in the beds is released back into the cabin at the beginning of each cycle change. While this was a simplification it was a conservative one since the impact on the humidity removal system was larger for this assumption than it would be for the real system.

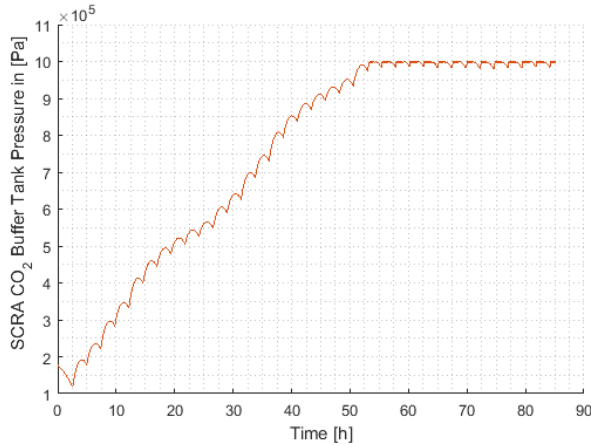
The simulation results for the partial pressure of CO<sub>2</sub> shown in Figure 6 cover the third day of the simulation from hour 48 to 72. In this case the third day was chosen because the CO<sub>2</sub> level requires more time to reach a repetitive profile than the humidity. While the second day still differed from the later days the third day was again a good representation for each of the following days.



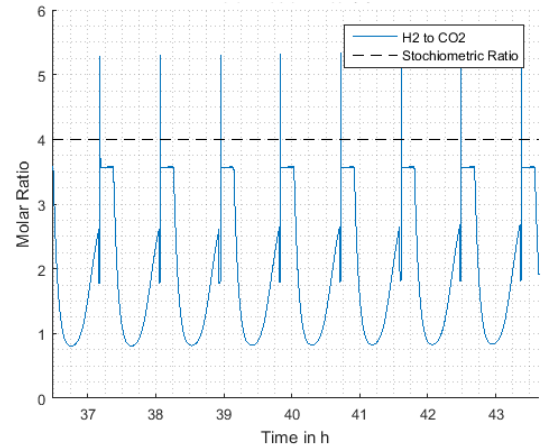
**Figure 6. ISS Partial Pressure CO<sub>2</sub> Simulation Results for the current ISS LSS configuration with ACLS.**

The small spikes that were observed in Node 3 and SM were a result of the CDRA air-save mechanism. Since the Russian system had a shorter cycle time the time interval between each spike was smaller. The larger spikes occurring in Node 3 were again a result of the exercise schedule of the crew. For the nominal ISS system (dashed black line) the CO<sub>2</sub> level was between 400 and 600 Pa which was higher than the expected value. The most likely cause for this was the underestimation of the CO<sub>2</sub> removal rate of Vozdukh. From the comparison of the nominal case and the case with ACLS the approximate possible reduction in partial pressure that could be achieved with ACLS was calculated to ~200 Pa.

In this case with ACLS the overall CO<sub>2</sub> level was lower compared to the nominal ISS case as shown in Figure 6. This led to concerns whether it was still possible to supply sufficient CO<sub>2</sub> to the Sabatier systems. In this case two Sabatier Systems were used in parallel, the US SCRA and the Sabatier system included in ACLS. The models for these two systems assumed that SCRA has a CO<sub>2</sub> buffer store that supplies the required CO<sub>2</sub> while ACLS is given a direct feed from the desorbed CO<sub>2</sub> of its own absorber beds. Therefore, the indicator if sufficient CO<sub>2</sub> was supplied to the Sabatier differs. For the US System the pressure inside the CO<sub>2</sub> buffer could be used while for ACLS the molar ratio between H<sub>2</sub> and CO<sub>2</sub> was used.



**Figure 7. CO<sub>2</sub> Supply to US Sabatier System.**



**Figure 8. CO<sub>2</sub> Supply to ACLS Sabatier System.**

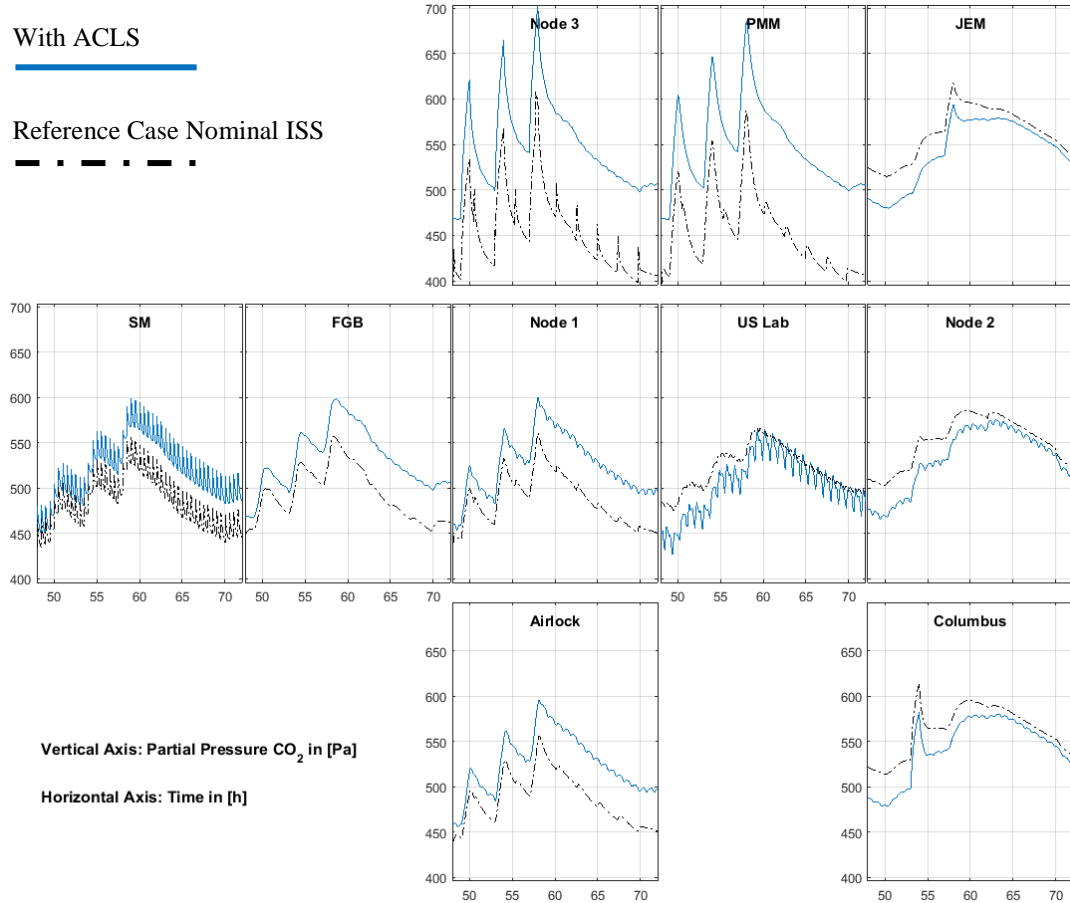
As Figure 7 shows the pressure in the CO<sub>2</sub> buffer store increased over time, till it reached the assumed maximum value of 1,000,000 Pa and CO<sub>2</sub> was vented into space. On the other hand, the molar ratio of the flow supplied to the ACLS Sabatier also remained CO<sub>2</sub> rich except for a single time step at each cycle change which can be neglected. Overall, this indicates that even though an additional CO<sub>2</sub> removal system was used the amount of CO<sub>2</sub> that each system removed was still sufficient to maintain the operation of the Sabatier systems. The reason for this is that generally an excess amount of CO<sub>2</sub> is available for the Sabatier reaction since too little H<sub>2</sub> is produced by the electrolyzers to process all the CO<sub>2</sub>. For this simulation it was assumed that both ACLS and SCRA are supplied the amount of H<sub>2</sub> that is produced during the production of O<sub>2</sub> for three crew members. This basically means that each Sabatier was supplied about half of the available H<sub>2</sub>. But that still left an overall excess of CO<sub>2</sub>. Therefore, it did not matter that Vozdukh was also active and removing CO<sub>2</sub> from the atmosphere since each Sabatier still received sufficient CO<sub>2</sub> for continuous operation.

## B. US CO<sub>2</sub> removal systems deactivated

The second test case assumed that all US LSS are offline except for the CCAAs, the detailed configuration used for the LSS in this case is shown in Table 4. Any LSS that is not mentioned is considered to be active in all cases.

**Table 4. LSS Hardware Status for the Second Case**

Node 3				US Lab			
CDRA	CCAA	SCRA	OGA	CDRA	CCAA1	CCAA2	ACLS
OFF	ON	OFF	Standby	OFF	OFF	OFF	ON



**Figure 9. ISS Relative Partial Pressure CO<sub>2</sub> Simulation Results for the case that the US LSS are offline.**

To make a comparison of the CO<sub>2</sub> level between the two cases easier this case shows the third day with the exact same time frame. Since ACLS is designed for three humans<sup>11</sup> while CDRA is designed for six<sup>14</sup> an increase in the partial pressure of CO<sub>2</sub> was expected for this case (blue line) compared to the nominal ISS (dashed black line). However, it could be observed that the US-Lab, Node 2, JEM and Columbus actually had a slightly lower partial pressure. This arose from the IMV flow setup and the location of the crew exercise activities. In the current IMV setup the US Lab, Node 1, FGB and SM were creating a loop and no air was moved directly from Node 1 to the US Lab. Instead the air first passed through the SM before it was transferred to the US Lab. While CDRA was located directly in Node 3, ACLS is planned to be installed in the US Lab<sup>3</sup> which was the assumed location for it in this simulation. Since the crew exercised in Node 3 and most of the CO<sub>2</sub> was produced during the exercises CDRA could react faster to this change and removed more CO<sub>2</sub>. On the other hand, it took a fairly long time for the change in the CO<sub>2</sub> level to move from Node 3 to the US Lab where ACLS was located. Additional to the time delay the CO<sub>2</sub> was spread out more until it reached ACLS than it was for CDRA which put ACLS at a disadvantage regarding the CO<sub>2</sub> removal rate.

## V. Conclusion

An analysis of the impacts ACLS will have on the atmosphere of the ISS was performed and it could be concluded that replacing CDRA with ACLS as CO<sub>2</sub> removal system will lead to a higher overall CO<sub>2</sub> level on the ISS with sizeable difference between the modules. However, the location of ACLS was unfavorable in the simulation with the current crew schedule. Therefore, repeating the simulation with a different crew schedule and exercise location is necessary to identify the exact impact of the location of the CO<sub>2</sub> removal system on the partial pressure of CO<sub>2</sub>. As a last step, a detailed ISS crew schedule can be used for the simulation to produce higher fidelity data. Furthermore, the possibility of using all CO<sub>2</sub> removal systems in parallel to achieve an overall lower level of CO<sub>2</sub> was explored. This proved to be an interesting approach since both Sabatier systems were still able to function normally while the CO<sub>2</sub> level on the station was reduced significantly. It might be worthwhile to further explore this as a possible configuration for the use of ACLS onboard the ISS.

The paper can also be seen as a proof of concept for a combined simulation of the atmospheric composition and LSS hardware in V-HAB. However further study will be necessary to decide how detailed the exchange between the different modules has to be modeled and how many volumes should be used to achieve optimal simulation results in a meaningful time frame. Furthermore, in future work the LSS subsystems of the ISS can be improved. For CDRA a model using the linear driving force is currently under development that should improve the capability of the CDRA simulation to better predict off nominal cases. While the models for the Russian systems definitely were the least well defined or validated models in the simulation it will not be possible to improve them without acquiring additional data. Likewise, the ACLS model should be improved once additional performance data or overall system test data become available. While the presented work focuses on the impact ACLS has on the atmosphere it would be possible to also model the impact it has on the water systems of the ISS. For that purpose however, the water processing systems of the ISS LSS will have to be added to the simulation. Finally, the ISS simulation itself can be improved by adding the thermal impact of the payloads and modeling the temperature of the atmosphere in greater detail.

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## References

- <sup>1</sup>Czupalla, M., "The Virtual Habitat - Integral Modeling and Dynamic Simulation of Life Support Systems," Ph.D. Dissertation, Institute of Astronautics, Technical University Munich, Munich, Germany, 2011
- <sup>2</sup>Czupalla, M., Zhukov, A., Mecsaci, A., Deiml, M., Beck, M., "Dynamic Life Support System Simulations with the Virtual Habitat," *AIAA 41<sup>st</sup> International Conference on Environmental Systems*, AIAA, Portland, Oregon, July 2011
- <sup>3</sup>Bockstahler, K., Matthias, C., Lucas, J., Witt, J., Hovland, S., Laurini, D., "Development Status of the Advanced Closed Loop System ACLS," *45<sup>th</sup> International Conference on Environmental Systems*, Bellevue, Washington, July 2015
- <sup>4</sup>Plötner, P., Roth, C., Zhukov, A., Czupalla, M., Anderson, M., Ewert, M., "Status of the Correlation process of the V-HAB Simulation with Ground Tests and ISS Telemetry Data," *AIAA 43<sup>rd</sup> International Conference on Environmental Systems*, AIAA, Vail, CO, July 2013
- <sup>5</sup>Weber, T., "Extension and correlation of a dynamic simulation model of the Life Support System of the International Space Station," B.Sc. Thesis, Institute of Astronautics, Technical University Munich, Munich, Germany, 2013
- <sup>6</sup>Hirschka, M., "Implementation and Optimization of the International Space Station Air Revitalization System at V-HAB 2.0," B.Sc. Thesis, Institute of Astronautics, Technical University Munich, Munich, Germany, 2015
- <sup>7</sup>Pütz, D., "Assessment of the Impacts of ACLS on the ISS Life Support System using Dynamic Simulations in V-HAB," M.Sc. Thesis, Institute of Astronautics, Technical University Munich, Munich, Germany, 2015
- <sup>8</sup>Son, C., Smirnov, E., Ivanov, N., Telnov, D., "Integrated Computational Fluid Dynamics Ventilation Model for the International Space Station," *SAE 35<sup>th</sup> International Conference on Environmental Systems*, SAE
- <sup>9</sup>Bockstahler, K., Funke, H., Brodt, K., Lucas, J., Witt, J., "Design Status of the Closed-Loop Air Revitalization System ARES for Accommodation on the ISS," *40<sup>th</sup> International Conference on Environmental Systems*, Barcelona, Spain, July 2010
- <sup>10</sup>Bockstahler, K., Lucas, J., Witt, J., "Design Status of the Advanced Closed Loop System ACLS for Accommodation on the ISS," *43<sup>rd</sup> International Conference on Environmental Systems*, Vail, Colorado, July 2013
- <sup>11</sup>Plötner, P., "Modeling of the ISS in V-HAB and Correlation with Flight and Ground Tests Data," M.Sc. Thesis, Institute of Astronautics, Technical University Munich, Munich, Germany, 2012

<sup>12</sup>Anderson, M., Ewert, M., Keener, J., Wagner, S., "Life Support Baseline Values and Assumptions Document," NASA/TP-2015-218570, Lyndon B. Johnson Space Center, Houston, Texas

<sup>13</sup>Link, D., Balistreri, S., "Inter-Module Ventilation Changes to the International Space Station Vehicle to support integration of the International Docking Adapter and Commercial Crew Vehicles," *45<sup>th</sup> International Conference on Environmental Systems*, Bellevue, Washington, July 2015

<sup>14</sup>Knox, J., "International Space Station Carbon Dioxide Removal Assembly Testing, " *30<sup>th</sup> International Conference on Environmental Systems*, Toulouse, France, July 10-13, 2000