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DYNAMIC LIFE SUPPORT SYSTEM SIMULATIONS WITH V-HAB

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Abstract

The dynamic life support system (LSS) simulation software Virtual Habitat (V-HAB) has been under development at the Technische Universität München since 2006. The MATLAB®-based V-HAB software suite dynamically simulates habitat life support systems and their interaction with a detailed human model, as well as the external environment of the habitat. Built upon an object-oriented framework, V-HAB provides the capability for holistic, multi-domain simulations for many applications in closed environments. V-HAB not only includes a detailed and environmentally sensitive human model, but also plant and algae models for the analysis of bio-regenerative LSS configurations.

This paper presents the current development status of V-HAB and shows results from simulations of the International Space Station LSS. The results show good agreement across several different disciplines and measurement values.

1. INTRODUCTION

Life support systems (LSS) are highly complex systems that are very expensive to design, build, test, and validate, both in cost and time. To ensure the safety, stability, and reliability of a LSS, engineers try to model and analyze the systems thoroughly before beginning detailed design and construction. In the past, the modeling and analysis methods used were based on static approaches, like worst-case design points and the equivalent system mass (ESM) metric. [1] These methods are based on empirical performance equations and the experience of LSS engineers. However, since most modeling approaches are static, they do not represent the actual environment in which the LSS will operate during its mission, which is dynamic.

Recent research has shown that dynamic simulations are advantageous over these static approaches. [2] Dynamic simulations lead to a better understanding of the operating range the system will need to cover as well as the transient behavior of the integrated system and its interacting sub-systems. This is important because in steady state analyses the LSS technologies are simply turned on and off, however in reality individual technologies, subsystems and integrated systems usually have startup and shutdown transients, as well as load-specific performance characteristics, sometimes with large time constants, thus deviating from the usually modeled steady-state performance.

Keeping the crewmembers inside a habitat or space suit alive and comfortable is the primary objective of any LSS. The interrelations and interdependencies between the human and the LSS are so pronounced, that the human can be considered a “subsystem” of the LSS. Therefore, just as it is important to know the dynamic behavior of all the LSS hardware involved, it is equally important to know the dynamic inputs and outputs of the human occupying the LSS. As a result, the presence of a sophisticated human model inside the modeled LSS is essential for the simulation to produce satisfying results.

The MATLAB® based, dynamic LSS simulation software V-HAB has been under development at the Technische Universität München (TUM) since 2006. V-HAB allows the dynamic simulation of habitat life support systems and their interaction with a human model and the environment of the habitat. V-HAB includes dynamic models of several physio-chemical (P/C) LSS technologies, bio-regenerative LSS technologies and a dynamic human model. By correlation with real LSSs such as the ISS ECLSS the tool has reached a high level of maturity. [3]

This paper presents results of simulations performed with a new, higher fidelity ISS LSS model than was used for the correlation described in reference 3.

2. THE VIRTUAL HABITAT SIMULATION TOOL

2.1. Overview

V-HAB is a dynamic, discrete-event simulation. It currently contains simulation frameworks for matter based models (matter flows, chemical and biological processes and physical effects) and thermal simulations (conductive and convective heat transfer). Radiative heat transfer is achieved through coupling with either commercial thermal analysis tools or, in the case of thermal simulations of moving objects on the surface of planetary bodies, with the TherMoS tool [4, 5], also developed at TUM. In the future it is planned to add a framework for electrical simulations.

To enable simulations in different technical and scientific domains, V-HAB is made up of four modules: a crew module containing a sophisticated and also dynamic physiological model of a human body, physical/chemical (P/C) and biological modules to model LSS technologies in these domains and finally an infrastructure module that ties all other modules together.

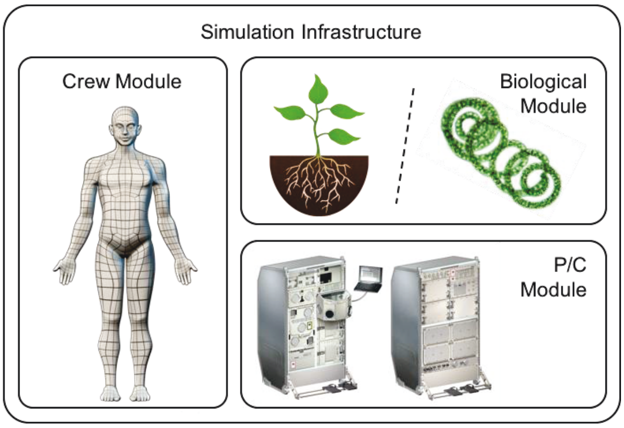


FIG 1. V-HAB Structure

2.1.1. Crew Module

The human model dynamically reacts on and impacts the simulated environment and therefore is the key element of any simulated LSS. The human model has five interconnected layers and each layer corresponds to a specific physiological function of a human body: A metabolic layer, a water/electrolyte layer, a cardiovascular layer, a digestive layer, a thermal layer and a respiratory layer.

The respiration layer is organized into three main components: lung, brain, and body tissue. The components are connected via the simulated blood flow, which is part of the cardiovascular model. The simulated respiration depends on the activity of the subject and the atmospheric composition of the surrounding environment.

The metabolic layer models the conversion of energy to the human body in form of carbohydrate, protein, and fat degradation. These inputs are provided by the digestive layer. There is a global parameter for the human model that determines the current activity level based on the percentage of maximum oxygen consumption ($\%VO_{2,max}$).

The water/electrolyte layer provides the water interface to the surrounding environment and calculates the water/electrolyte balance of the human body. A kidney model regulates the electrolyte concentration in the bodily fluids and a thirst model triggers the uptake of water by the human. In case of insufficient uptake due to a simulated water shortage, the water balance layer can predict the resulting performance detriment of the human model.

The thermal layer is a lumped parameter model that can be adapted to a variable number of nodes depending on the simulation requirements. Temperature prediction of these body parts depends on the environmental condition, the activity level, and the availability of water for cooling (sweating). The underlying human thermoregulatory model is based on a NASA implementation of the Wissler human thermal model [6].

The digestive layer supplies the rest of the human model with the necessary nutrients and water extracted from consumed food. The food is taken in through an interface with the corresponding food store in the LSS model. The second interface of the digestive layer is the return of feces and urine to the waste and water management systems of the LSS in quantities and make up according to the food and water intake.

The cardiovascular layer interconnects the other layers by simulating blood flow and cardiac output. These values are mainly utilized in the respiratory, metabolic, and thermal layers.

2.1.2. Biological and P/C Module

The biological module includes plant models for 12 species of plants and a model of *Spirulina platensis* algae. The plant model is based on the Modified Energy Cascade (MEC) model [7, 8]. The plant module is currently in the process of being enhanced further to improve the predictive capabilities with respect to gas exchange due to evapotranspiration and photosynthesis. [9]

The P/C module has a library of existing and conceptual LSS components, some of which are used in the ISS LSS model described in the later sections of this paper.

2.1.3. Infrastructure Module

The infrastructure module is the backbone of all V-HAB simulations. It provides the framework for the interconnection of the different modules and models via flow rate solvers. Also included are mechanisms which monitor the overall mass in the simulated system to ensure the conservation of mass within the overall model and also to identify unwanted accumulations of matter inside buffer tanks or technologies. The infrastructure module also provides an intelligent, global simulation timer that can set a variable time step for each simulation object, depending on the current rate of change of the individual object. This ensures fast simulation speeds in phases of relative stability or inactivity and a high resolution of results during dynamic periods, like opening valves or mode switches within a technology model.

2.1.4. Use Cases

Using V-HAB, a systems engineer can gain deep insight into the dynamic system behavior at a very early stage during product development, reduce the number of hardware tests required in the detailed design phase or evaluate the effects of operational decisions during the actual mission. Each of these use cases of course requires an increasing amount of effort to be put into the system model.

Through various cooperative projects with LSS hardware designers [10], manufacturers [11] and operators V-HAB has proven its capabilities.

2.2. Modeling Philosophy

When creating a model in V-HAB the modeling philosophy follows a bottom-up approach. This means first creating a very detailed, low-level model of a subsystem or component, preferably using only first principles to model the physical, chemical or biological effects involved.

Using the simulation results from these base models, more abstract models can be derived that depict an entire technology chain or subsystem with multiple processes. This abstraction process can then be repeated on the technology level to create models of entire life support systems.

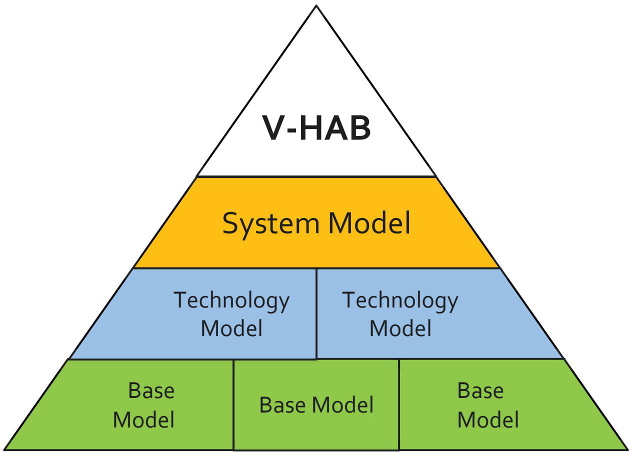


FIG 2. V-HAB Modeling Philosophy Pyramid

These different modeling levels result in simulations that run at very different simulation speeds. Base models are usually significantly slower than real-time, technology models run at speeds around real-time and system models must be significantly faster than real time to enable the kind of analyses outlined in the previous section.

V-HAB includes a set of several solvers that are tailored to the requirements of each of the three simulation levels. The increase in simulation speed of the system level simulations, however, comes at the price of simulation accuracy, but this is acceptable for most uses cases. For instance, a simulation of the International Space Station's life support system, as will be presented in the following sections of this paper, does not require the system water balance to be 1 mg accurate.

2.3. Simulation Architecture

The V-HAB *core* level includes *modelling classes* as well as *infrastructure classes*. *Infrastructure classes* contain the basic software structure of V-HAB that enables the simulation itself. This includes commonly used tools, the different solvers and the global timer, among others. The *modeling classes* contain the basic classes for building models that will be described in greater detail in the following sections.

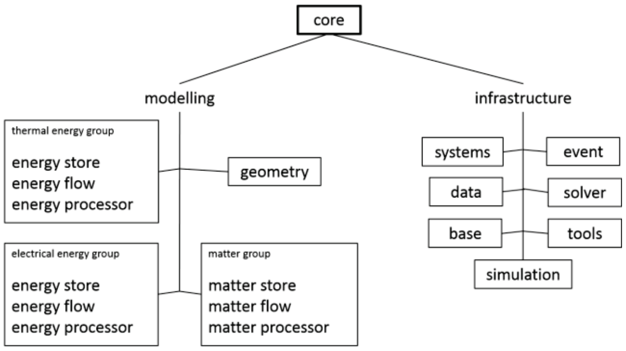


FIG 3. V-HAB Core Architecture

2.3.1. Matter Stores

Matter Stores are essentially a representation of a tank. As with a physical tank, matter inside a store can be either in a solid, liquid or gaseous state. *Matter Stores* therefore always contain child objects called *Matter Phases*. These represent an amount of matter in a uniform state. So for example a *Matter Store* filled partially with water and water vapor would contain a liquid *phase* object and a gaseous *phase* object. A *Matter Store* can have two phases of the same state as well, to model an electrolyzer for instance. This *Matter Store* would have on liquid *phase* for the water and two gas *phases* for the produced hydrogen and oxygen.

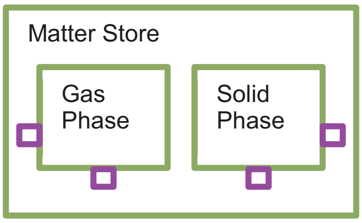


FIG 4. Matter Store

The *Matter Stores* use the general matter properties from the *core* classes to calculate the properties specific to the matter contained in the store. These properties include temperature, (partial) pressure, heat capacity and volume.

It is important to note, that the matter properties inside a *store* cannot be changed by the *store* itself, but only through defined interfaces from the outside. This is to ensure that no matter is created or destroyed by inexact programming.

2.3.2. Matter Flows

Matter Flows describe the properties of moving matter inside the simulated system. They are used to connect matter stores, components and subsystems with each other. The main property of a *Matter Flow* is the flow rate, others include partial pressures and temperature. As with the *Matter Store*, a flow cannot change its matter properties. The flow rate is changed from the outside by the flow rate solver and the matter properties depend on the content of the *Matter Stores* to which the flows are connected.

2.3.3. Matter Processors

Matter Processors are the only objects that can manipulate the matter content and state of other objects. There are three different kinds of Matter Processors: *flow to flow* (f2f), *phase to phase* (p2p) and flow to phase / phase to flow. Since the latter processor is used to extract and merge matter from phases, it is designated an *extract/merge* (exme) processor to clarify its bidirectionality.

As the name suggests, *flow-to-flow* processors can change the properties of a *matter flow*. An example for this would be the model of a fan that increases the pressure and temperature of a flow.

FIG 5. Flow-to-flow processor

Phase-to-phase processors are used inside *Matter Stores* to transfer matter from one *phase* to another. In the exemplary tank filled with water and water vapor, an evaporation function would use a *p2p* processor to subtract mass from the liquid water *phase* and add it to the water vapor gas *phase*. *Phase-to-phase* processors can also be used to model chemical reactions inside a phase.

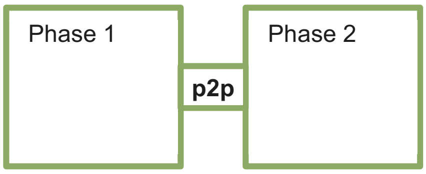


FIG 6. Phase-to-phase processor

The *extract/merge* processors are the interface between *phases* and *flows*. The flow rate of a connected *flow* is an input for the *exme* processor which in turn provides the *flow* with the information about the flowing matter and also adds or subtracts the corresponding amount of matter from the *phase* to which it is connected. For more complex models, several *exme* processors can be attached to a single *phase*, however only one flow can be connected to each *exme*.

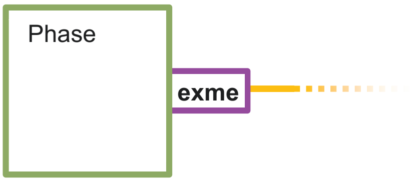


FIG 7. Extract-merge-processor

2.3.4. Systems and Branches

The *Systems* class provides the framework for the grouping of stores, flows and processors. It is not to be confused with a physical system or subsystem of a LSS. Inside an object instantiated from the *Systems* class the actual connection between *stores*, *flows* and *processors* is made. Additionally, connected flows are grouped into *branches*. A branch is defined as the collection of *flows* and *processors* between two *exme* processors. The *Systems* class also provides interfaces to which other systems can be connected on the next higher hierarchical level of the simulation model.

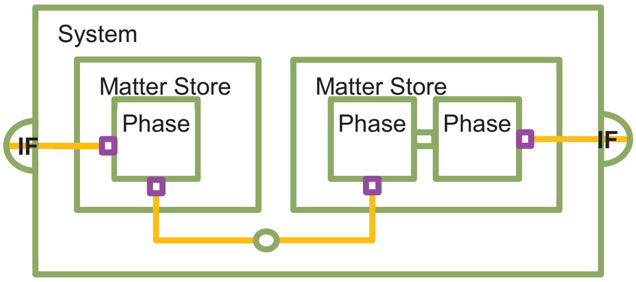


FIG 8. V-HAB System with Branches

2.3.5. Solver

For each matter flow *branch*, a *solver* object can be created and assigned. This means that for every *branch*, the desired *solver* and its properties can be separately chosen. Besides a pseudo-solver (called *linear* solver, calculating reasonable, but incorrect flow rates), the *iterative* solver (which is slower, but calculates correct flow rates), and the *manual* "solver" (which sets fixed flow rates), in-depth finite difference method (FDM) solvers are available that are very slow, but also calculate correct flow rates e.g. for compressible fluids. [12] Additional features and solvers are planned for the future, e.g. the possibility that several branches are solved together by a more global solver, rather than independent from each other.

As mentioned previously, the time step in V-HAB is variable. This means that every solver, phase, or subsystem can set its own time step. The global timer object sets its own next time step according to the smallest time step that was set by any of the registered components. Three entities within V-HAB can trigger an update:

Flow Rate Solver: a solver sets its own time step, after which the "update" method of the solver is called again. If the solver recalculates the flow rate (and accordingly the pressure drops in the *f2f* processors etc.), it calls the branch it is assigned to and sets the new flow rate. This triggers a method called "massupdate" in the connected phases, which updates the partial masses in those phases..

Phase: each *phase* sets its own update time step, according to the sum of flow rates vs. the total mass stored within the *phase*. Subsequently, this time step is set for the whole *store* this phase belongs to. This means that all *phases* within one *store* update according to the smallest time step set.

Subsystem: for e.g. control purposes (check levels of a substance, open/close valves etc.), a subsystem can set a fixed time step with which its *exec* method is called. During simulation, the subsystem can also dynamically change this time step. If in such an *exec* method e.g. a valve is closed, i.e. the pressure drop of a *f2f* processor is changed, this processor automatically calls the *branch* it is assigned to and sets it as "outdated", which means that the *update* method of the assigned solver is called immediately at the end of the current time step.

3. THE INTERNATIONAL SPACE STATION LIFE SUPPORT SYSTEM MODEL

The international space station (ISS) currently is the only outpost of humanity outside of earth's atmosphere that is continuously inhabited and therefore it is also one of the few places where a life support system is permanently required to sustain human life. That makes it a very interesting system for modelling and simulation in V-HAB and several iterations of the ISS LSS have been created in V-HAB in the past. Another reason why the space station is interesting for V-HAB is that it actually exists. Quite a few of the other systems that have been modeled using V-HAB are just design concepts, which makes it difficult to verify the simulations since there is no test data available yet. For the ISS however a large amount of telemetry and test data is available which makes it possible to verify the simulation and show that the basic V-HAB modelling approach works and reflects actual behavior of the system to a certain degree of accuracy.

This paper will only present an overview of the ISS LSS subsystems that where modeled, for a more detailed description please refer to references 13–18.

3.1. Overview

FIG 9 gives an overview of all LSS systems currently deployed on ISS and their location within the space station. The location is important with respect to the gas flow paths between the modules and the crew worksites, since these are where the metabolic output is introduced into the system.

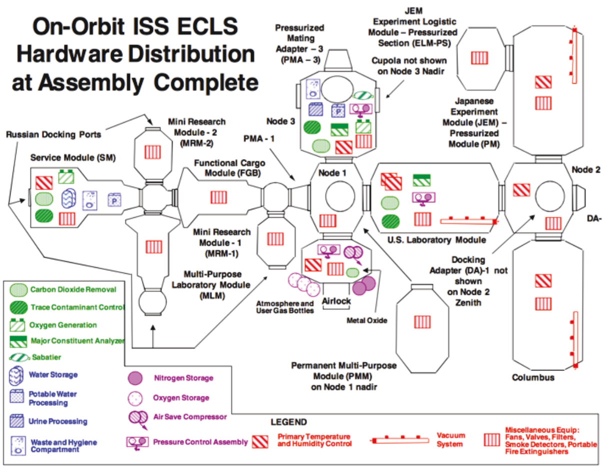


FIG 9. Current Configuration of the ISS Life Support System [19]

3.2. Modeled Subsystems

The following section describes the LSS subsystems that are currently included in the V-HAB ISS model. Life support systems in general can be divided into four main subsystems: Air revitalization, water processing, waste management and food provision. The results presented in this paper focus on the atmospheric conditions inside the ISS, therefore the waste management and food provision subsystems are not described any further.

In terms of the modeling levels described in section 2.2, the overall model is a mix of base and technology models. Some processes like the CO_2 adsorption are very accurate physical process models, while for instance the humidity removal system's water removal flow rate is based on a curve fitting of flight data.

An important aspect of the models is, that the different operational modes for the different subsystems are depicted. Some subsystems run continuously while others are operated in a batch mode. This has a great influence on the overall system dynamic.

3.2.1. Atmosphere Revitalization System (ARS)

3.2.1.1. Carbon Dioxide Reduction Assembly

The Carbon Dioxide Removal Assembly (CDRA) uses two zeolite 5A beds to remove carbon dioxide from the station atmosphere. Two additional zeolite 13X beds are used to remove the remaining humidity from the process air before the 5A beds since the adsorption process on the zeolite favors water over CO_2. To achieve continuous CO_2 removal, the system switches between the two adsorbent beds every 144 minutes [20]. While one is integrated into the cabin airflow, the other is connected to the vacuum of space for desorption. An air save pump is included to minimize the loss of gas during desorption.

There is always a zeolite 13X bed in front and one behind the 5A bed. The one in front removes the humidity from the inflowing cabin air as described above, the one behind is loaded with humidity from the previous cycle and is desorbed by the dry, CO_2-lean air leaving the 5A bed.

The adsorption process is modeled using a finite volume model of the beds themselves and the Toth isotherms for zeolite 13X and 5A governing the linear driving force. [11]

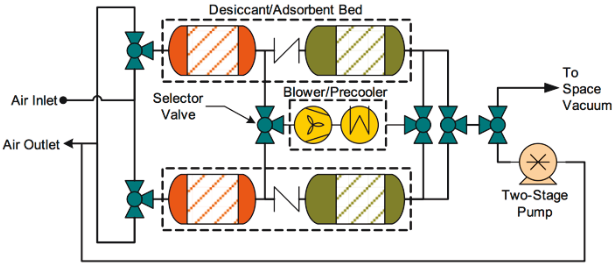


FIG 10. CDRA schematic [20]

3.2.1.2. Common Cabin Air Assembly

The common cabin air assembly (CCAA) uses a condensing heat exchanger (CHX) to remove humidity from the cabin air. The amount of air passed to the CHX is controlled by the temperature check control valve (TCCV) that regulates the air flow based on the current humidity in

The control function of the TCCV is modeled with an interpolation that calculates the flow rate that should pass through each branch based on the TCCV valve angle which is set by a control logic based on the current humidity.

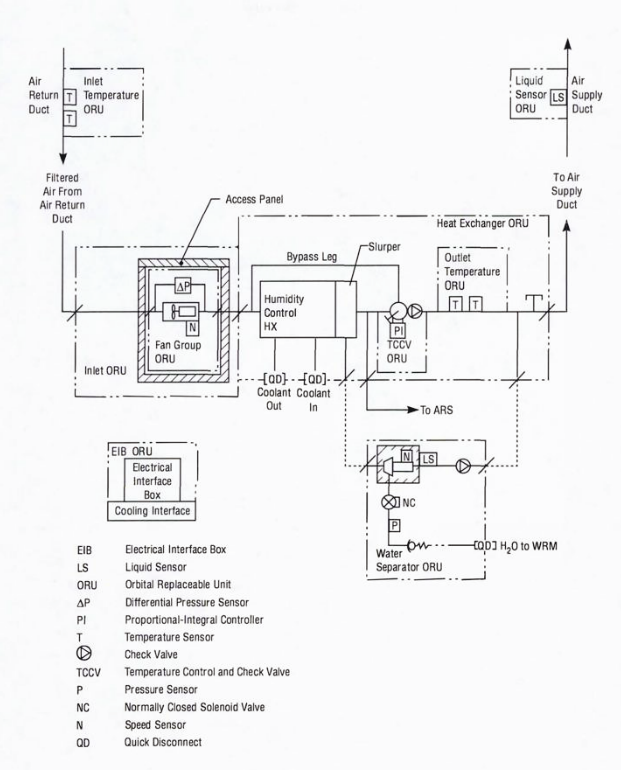


FIG 11. Common Cabin Air Assembly Process Schematic [21]

3.2.1.3. Sabatier CO_2 Reduction Assembly

The Sabatier Assembly takes in waste H_2, which is a byproduct of the oxygen production system described in section 3.2.1.4, and CO_2 from CDRA (section 3.2.1.1) and combines them to form H_2O and CH_4. The reactor products are cooled in a heat exchanger using cabin air. Here the produced water vapor is condensed. The liquid H_2O and CH_4 are then separated. The CH_4 is vented to space and the water is input to the ISS water management system.

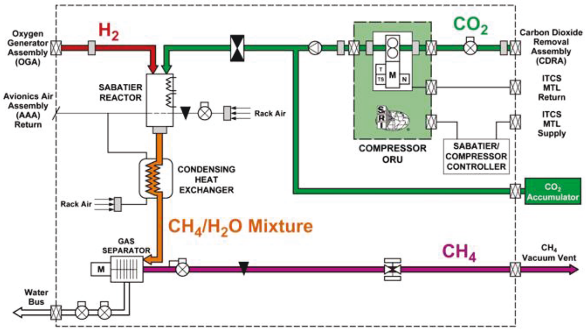


FIG 12. Sabatier Reactor Schematic [22]

3.2.1.4. Oxygen Generation Assembly

The oxygen generation assembly (OGA) and the Russian Elektron VM both use an electrolyzer to generate oxygen from water and are therefore also modeled by one subsystem file that uses an input to decide if it should use the values for OGA or for Elektron. The values for the oxygen production capability as well as the set points for the upper and lower oxygen limit were taken from [23]. However the oxygen production aboard the station is actually controlled by a human operator from ground control and takes a lot of variables into account while not having a specific and generally applicable rule to the oxygen production. Therefore, the control logic for the V-HAB model can only try to emulate what a human operator would do and will not always yield the same results.

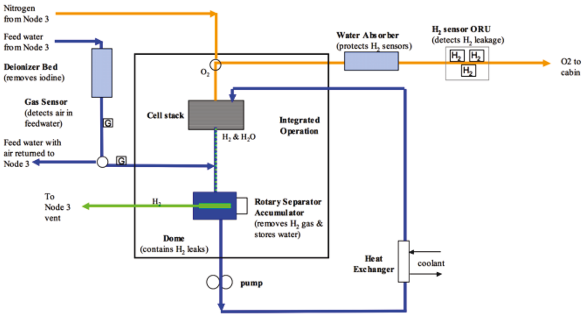


FIG 13 Oxygen Generation Assembly Schematic [24]

3.2.1.5. Vozdukh and Elektron VM

These two Russian systems correspond to the American CDRA and OGA respectively. Since we were not able to obtain detailed specifications for either system, the models for them are derivatives of the US models. The only changes that were made are in the modes of operation and general efficiency, which was reverse engineered from flight data.

3.2.2. Water Recycling System

The water recycling system (WRS) is modeled in V-HAB and its subsystems and functions are described in reference 25. Since this paper focuses on the atmosphere revitalization subsystem, the WRS will not be described in further detail.

3.3. Overall System Model

In past publications the ISS model used had one single *store* representing the entire interior volume of the ISS. While this is sufficient for top-level simulations, there was a desire to enhance the accuracy of the model. Therefore, a new model was created that uses multiple *stores*. This also meant a distribution of LSS technologies into different modules, the addition of an inter-module ventilation (IMV) model and a location property for the crew model to determine in which space station module the six crewmembers are at a given point in (simulated) time.

FIG 14 shows the model setup. Not every single module of the ISS was modelled as a store, some modules do not contain any LSS-relevant hardware and are just connected to the ventilation loops. These were grouped together into one *store*. The colored boxes in FIG 14 show how the actual modules are grouped together in the simulation model and their respective interior volumes. Please note that the values given are not the pressurized volume, but rather the free gas volume since this is the relevant value for LSS analyses. The image also shows the default location for all six crewmembers, the direction of IMV flow and the location of key LSS technologies.

One of the most prominent changes on system level model compared to the previous ISS models is the addition of a coolant water store with all necessary branches to actually supply the coolant to the subsystems. This allows the calculation of all temperature influences on the coolant water loop of the ISS which will be useful once the thermal systems are modelled since this is one of the interfaces between the ARS and thermal systems. Apart from that some smaller changes have been made like the addition of air save branches from the CDRA back into the ISS cabin.

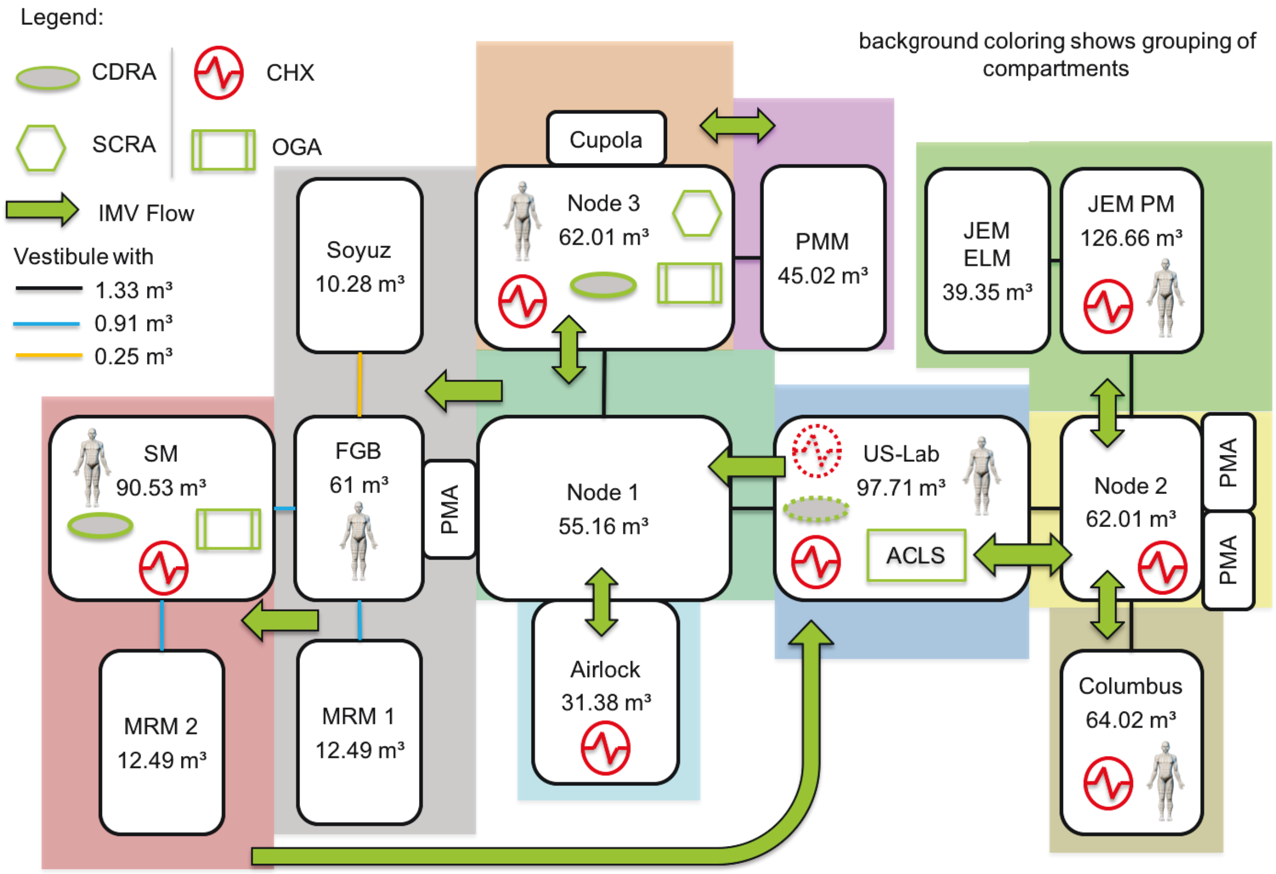


FIG 14. Overall ISS System Model. The colored boxes represent a single simulated volume.

3.4. Limitations

Every model is an abstraction of reality. In the interest of simulation speed and necessary effort for modeling, some effects and mechanisms are only modeled in a reduced fidelity or not at all. The following paragraphs summarize the limitations of the V-HAB ISS model.

There are some general limitations that are inherent to the way the basic V-HAB simulation architecture is set up. One of them is the assumption, that all *matter stores* are ideally stirred containers. It would be possible to create non-homogenous bodies of matter by just combining several stores with each other, but that is very cumbersome in terms of programming overhead. Also only convective and advective heat transfer is modeled in the current ISS model, the inclusion of a thermal solver for conductive heat transfer is still work in progress.

There is currently no diffusion solver in V-HAB, therefore the connections between the space station modules are modeled as discrete mass flows representing the intra-module ventilation fans only. The connection via the module hatches is not modeled, since there is no forced air movement through them. This leads to a very slow propagation of absolute pressure changes throughout the model.

Simplifications that were made to reduce the programming complexity are the neglecting of trace contaminants both in the cabin atmosphere as well as the water supply.

The human model assumes that all of the sweat produced by the crewmembers evaporates immediately and completely.

Other limitations arise from the source material for the models. Since it is difficult to access detailed specifications for components that were manufactured by space agencies' industrial partners, most models are based on published information regarding general values like tank sizes pipe diameters and length. Model validation was mostly done using ground test data, but these are usually twenty or more years old and may not be representative of the system on orbit any more. Very little information was available on the Russian systems and no ground test or flight data at all. However, since they are functionally very similar to the American systems, the models were derived from the US system models and adapted where necessary.

4. SIMULATION RESULTS AND DISCUSSION

Simulation results for individual subsystems have been presented in previous publications [3, 26], therefore this paper will focus on the system-level simulations of the ISS life support system.

To enhance readability, the next four sections will describe the results for four simulated values: CO_2 partial pressure, O_2 partial pressure, relative humidity and absolute pressure. The graphs actually showing the results will be given in section 4.5. Each graph contains 10 subplots, one for each of the simulated modules of the ISS. There are two graphs for each simulated value. The first covers a time span of 24 hours after the system has reached its dynamic steady state. This happens after approximately 72 hours. The second graph covers the first 100 hours of the simulation. This shows how the simulated system reaches its cyclical steady state. The following table shows the initial conditions present in the simulated life support system.

TAB 1. Initial conditions in simulated system

O_2 partial pressure	20.954,00 Pa
CO_2 partial pressure	250,24 Pa
Relative Humidity	39,62 %
Absolute Pressure	100.710,00 Pa

4.1. CO_2 Partial Pressure

The partial pressure for CO_2 in this simulation reaches fairly high levels but still remains below the 180 day limit for the ISS of 706 Pa mentioned in reference 27. In the 24 hour plot (FIG 15) distinct spikes in CO_2 partial pressure can be seen for the times when crewmembers exercise. Two crewmembers always exercise at the same time and also in the same module: Node 3. This is the reason why the CO_2 spikes are the highest in this module. The other modules also show these spikes, but they are a lot lower due to the distribution of the cabin atmosphere via specific *branches* that model the intra-module ventilation (IMV).

The ripple that can be observed in the Russian Service Module (SM) is produced by the operations principle of the Vozdukh CO_2 removal system as described in chapter 3.2.1.5. As can be seen from FIG 14 the airflow from the Service Module is directed back to the US Lab, therefore the ripple produced in the SM can be seen in that plot as well. Due to the large volume of the US Lab and its connections on both sides, the ripple is dampened out and no longer visible in the other modules.

In the 100 hour plot (FIG 16) a larger scale, repetitive pattern can be seen. This is due to the simulated crewmembers having the same schedule every day, consisting of sleep, a nominal workday including 1 hour of exercise and a following recovery phase. The only variation is the time of day when each individual crewmember exercises. The plot also shows, that the initial parameters that were arbitrarily set are not representative of the cyclic steady state levels. The CO_2 partial pressure in all modules rises for the first three days of the simulation.

4.2. O_2 Partial Pressure

The 24 hour plot of O_2 partial pressure (FIG 17) shows an almost inverted behavior to that of the CO_2 partial pressure. The three distinct downward spikes during crewmember exercise can clearly be seen. As in the CO_2 partial pressure plots, the spikes are more pronounced in Node 3 than in other modules. The ripple in the SM is only due to changes in absolute pressure caused by Vozdukh. Since the absolute pressure changes only propagate through the model very slowly, this ripple is not observable in the other modules.

In the 100 hour plot (FIG 18) a declining trend in oxygen partial pressure can be observed. While this may look alarming at first, the explanation here lies in the mode of operation for both the US OGA as well as the Russian Elektron VM. These technologies are operated in a non-continuous mode, meaning they are only turned on to maximum levels when necessary. The rest of the time the both run in a low power mode, still producing oxygen, but not enough to offset crew consumption. In reality, the mode switching is done manually by ground controllers. In the model, a simple controller was implemented that turns them on and off, based on partial pressure thresholds. In the 100 hours shown in FIG 18, the O_2 partial pressure does not drop below the lower threshold that would activate these two systems. This would happen after about 300 hours, when the partial pressure reaches 19.500 Pa.

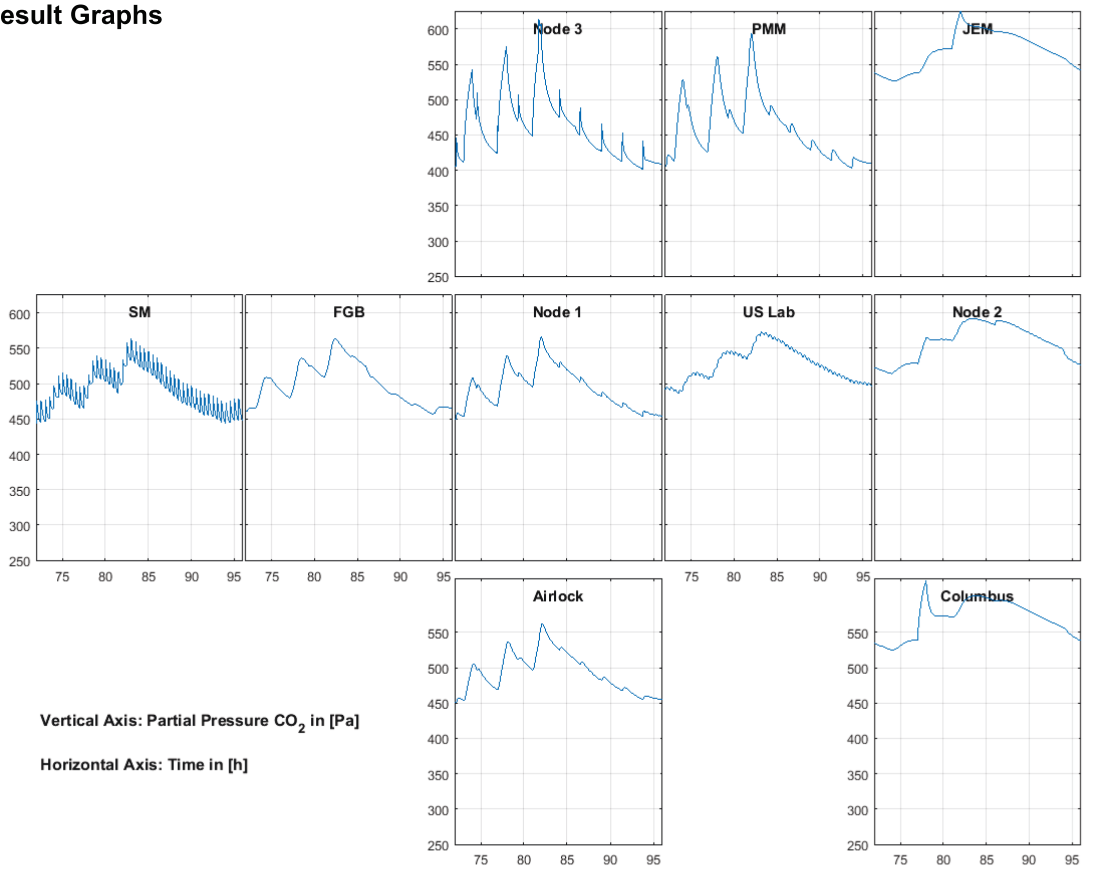
4.3. Relative Humidity

The main driver for relative humidity (RH) levels inside the station is again the crew. During times when the crew is exercising, the RH rises as high as 60 %, as can be seen from the 24 hour plot in FIG 19. Upon closer examination it may seem surprising at first that some of the spikes in certain compartments are more pronounced than for their neighboring compartment. For example, in the FGB the middle spike is higher than in Node 1 or the SM. This is a result of the crewmember working in FGB returning there after finishing the exercise. At that point the crewmember's metabolism is still in recovery and therefore produces additional humidity, which results in the more pronounced effect on this module compared to the neighboring one. The same is true for the higher spikes seen in Columbus and the Japanese module. Overall the humidity remains within the limits specified for ISS and is mainly within 35% to 45%. In reference 27 40% relative humidity is mentioned to be the nominal case for the ISS. In Node 3 during the night the humidity sometimes drops down to ~30% as a result of the CDRA humidity adsorber beds.

4.4. Absolute Pressure

The total pressure plots (FIG 21 and FIG 22) for the ISS interior volume reflect the behavior from the flight data shown in reference 16. Here the service module pressure was subjected to very large and fast oscillations, while the remaining compartments have a steadier pressure. The SM oscillations are again caused by Vozdukh, which has a shorter cycle time than CDRA and a less powerful air save pump. The remaining spikes in the total pressure can be explained with the daily activity profile of the crew. Overall the remaining pressure differences between the different modules are unrealistic. As described in section 3.4, the connections between the different modules are currently not "fast" enough to equalize the pressure inside the entire volume. Instead the relies solely on the difference in density resulting in different ventilation mass flows because these are volumetric flow rates. However, for any specific time during the simulation this difference is never larger than ~200 Pa which is only 0,2 % of the total pressure and therefore can be considered small enough to be neglected.

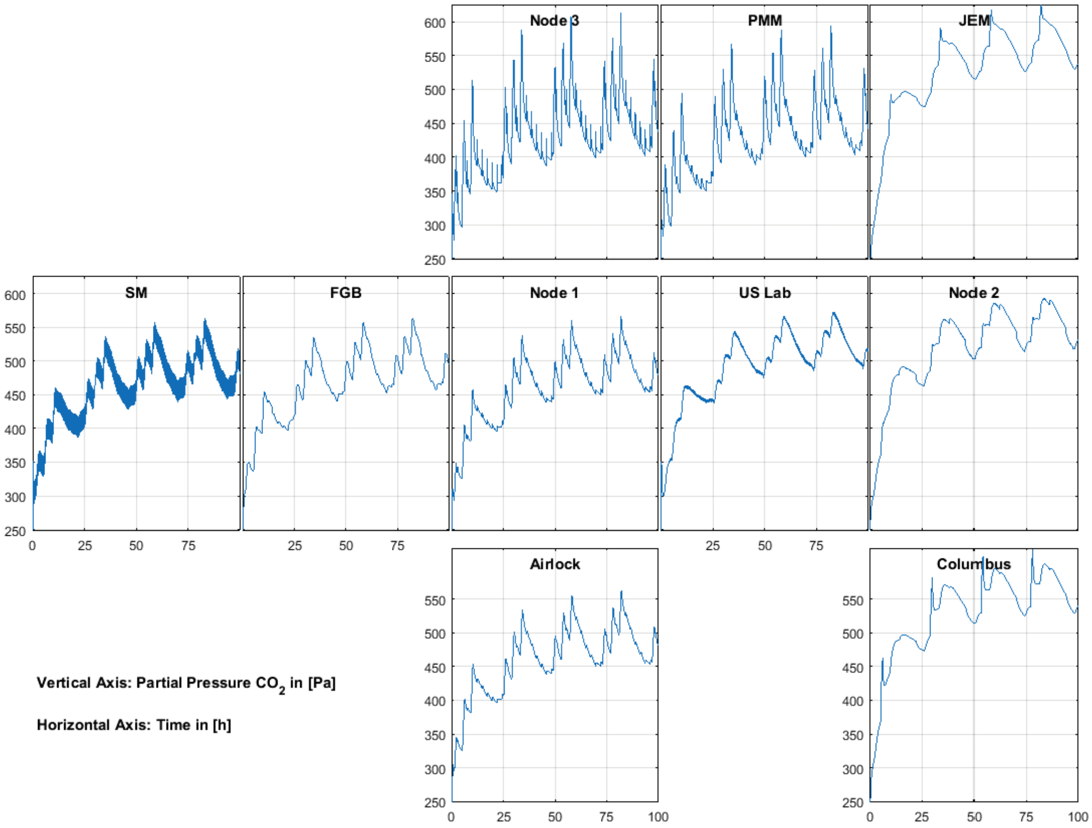
4.5. Result Graphs



Vertical Axis: Partial Pressure CO_2 in [Pa]

Horizontal Axis: Time in [h]

FIG 15. CO_2 partial pressure in each simulated ISS module over 24 hours



Vertical Axis: Partial Pressure CO_2 in [Pa]

Horizontal Axis: Time in [h]

FIG 16. CO_2 partial pressure in each simulated ISS module over 100 hours

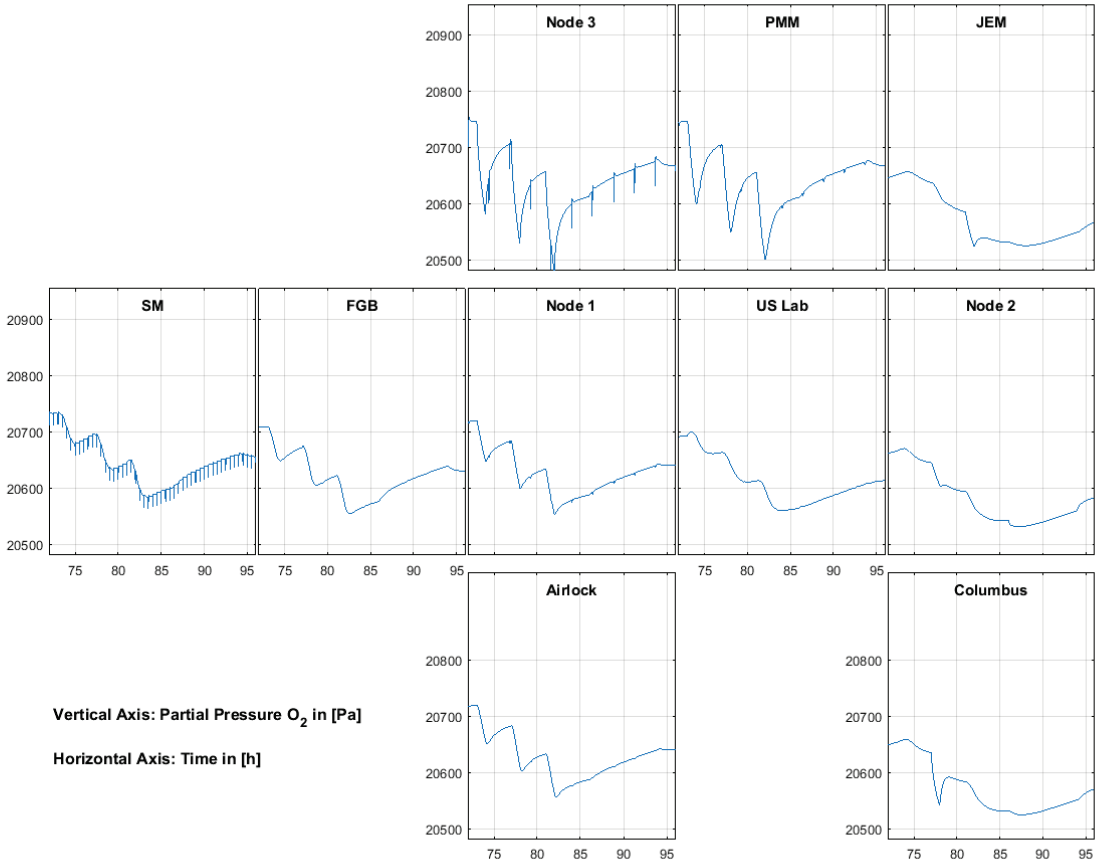


FIG 17. O_2 partial pressure in each simulated ISS module over 24 hours

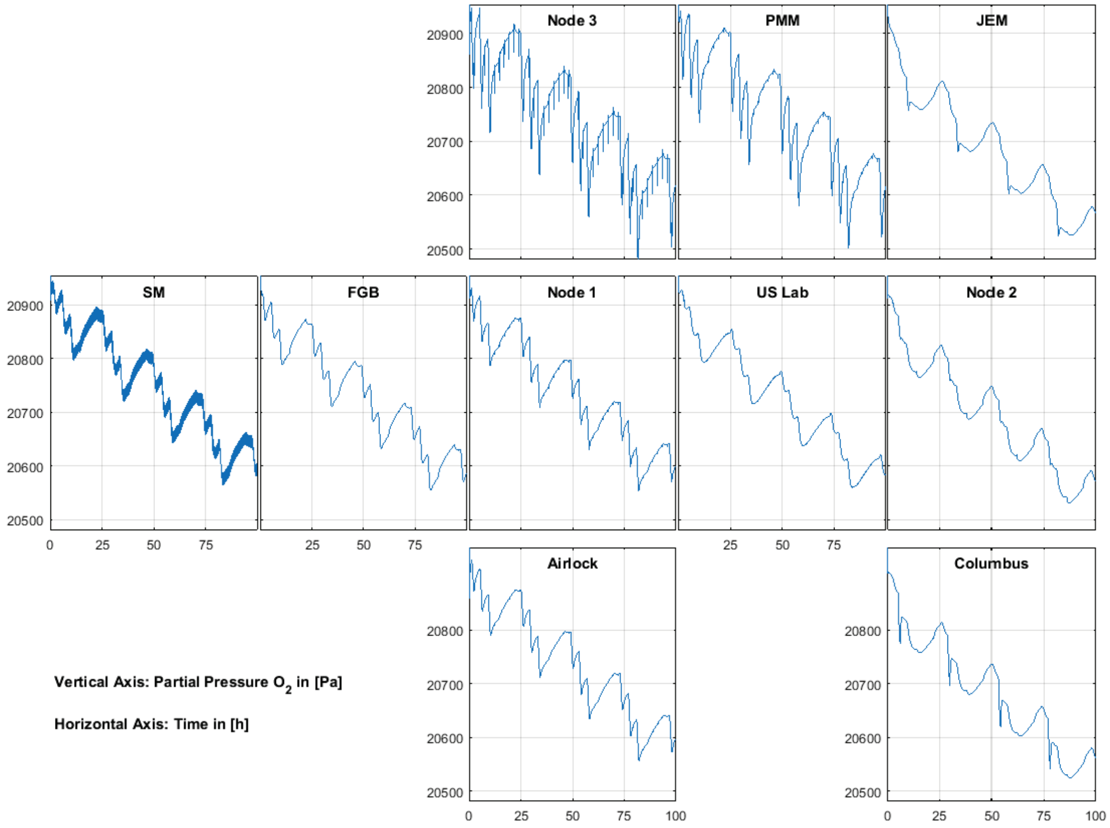


FIG 18. O_2 partial pressure in each simulated ISS module over 100 hours

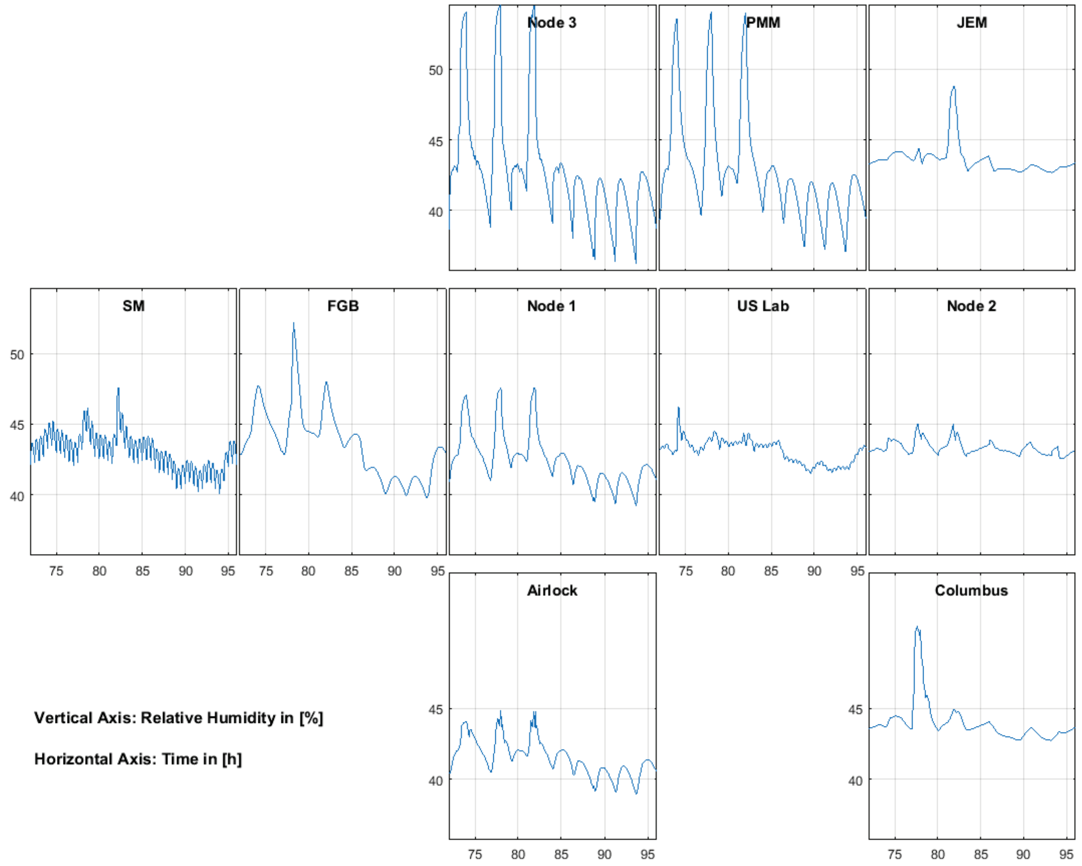


FIG 19. Relative humidity in each simulated ISS module over 24 hours

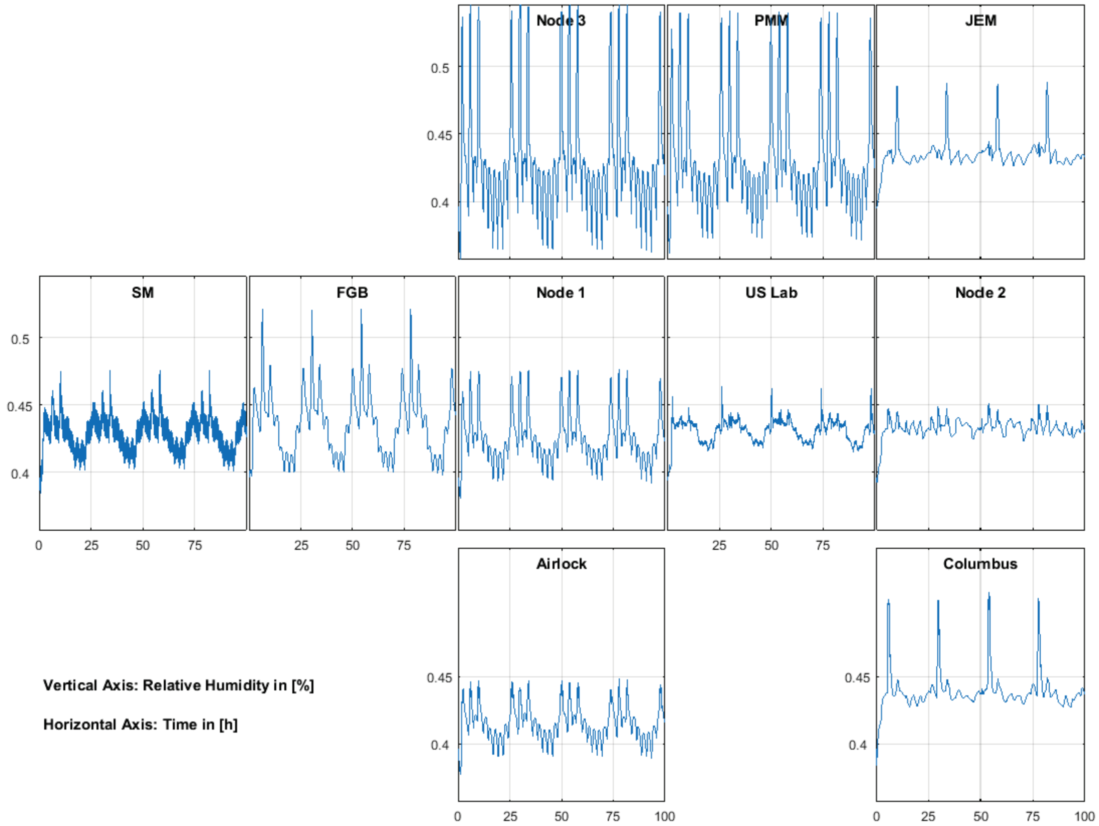


FIG 20. Relative humidity in each simulated ISS module over 100 hours

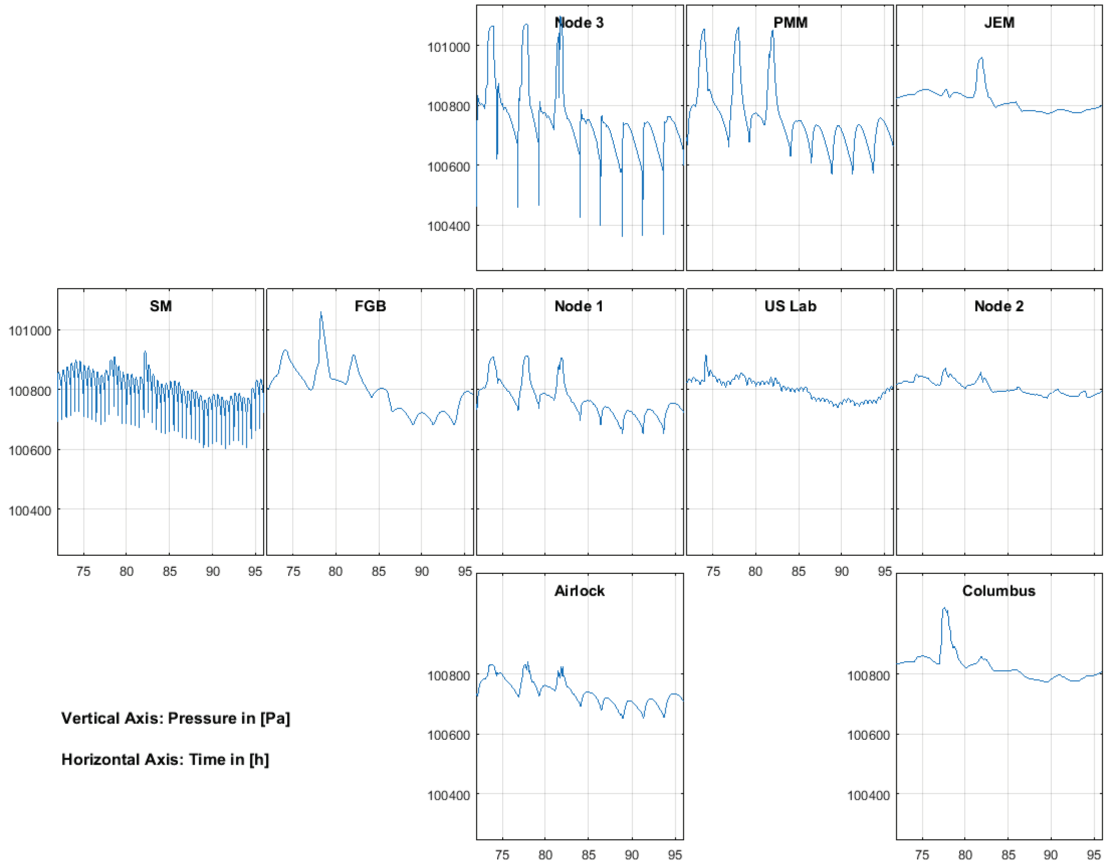


FIG 21. Total pressure in each simulated ISS module over 24 hours

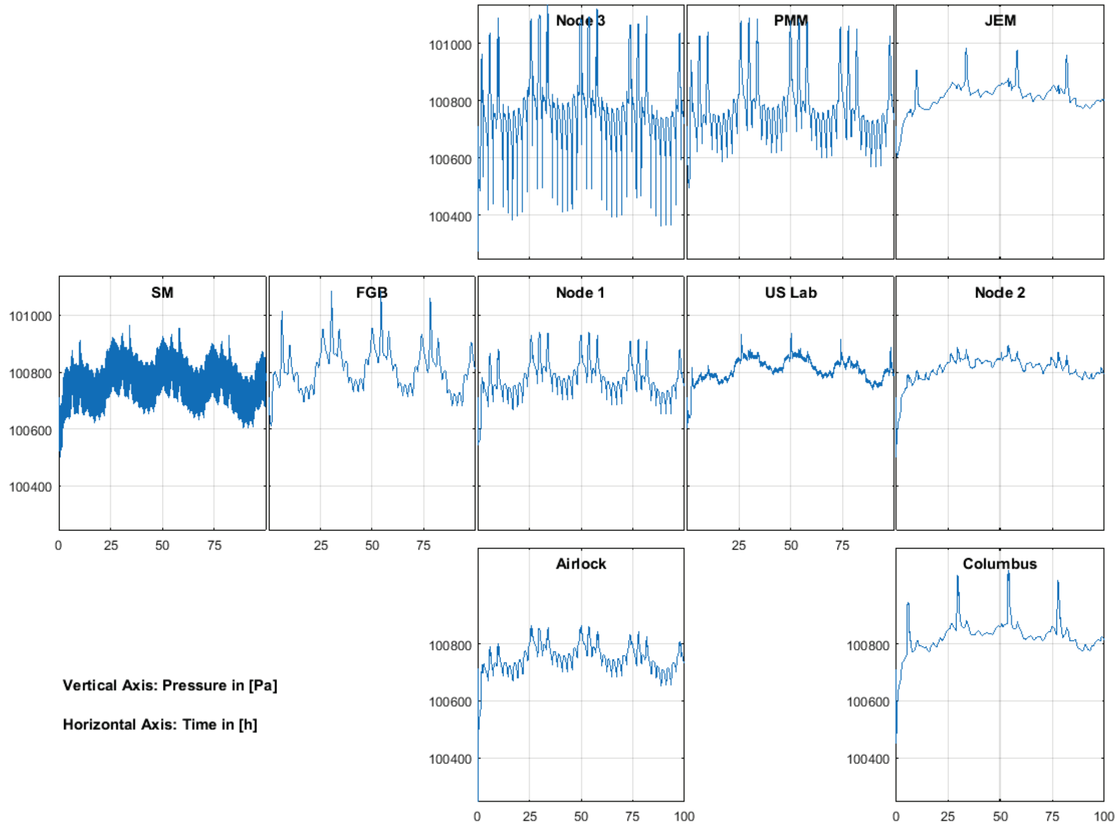


FIG 22. Total pressure in each simulated ISS module over 100 hours

5. CONCLUSION AND FUTURE WORK

The results show that V-HAB can be successfully employed to analyze complex processes in life support systems. The behavior of the ISS LSS could be reproduced with the added complexity of a multi-volume simulation, in comparison to past, single-volume simulations. The results also show the effect the human inhabitants have on the conditions inside the space station.

In the near future, the created ISS model will be used to evaluate the impact the new European Advanced Closed Loop System will have on the rest of the ISS LSS, specifically in terms of oxygen partial pressure and humidity. Also NASA has voiced interest to include V-HAB in a water tracking tool for the ISS.

The process of enhancing the existing models and adding of new capabilities is ongoing.

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7. REFERENCES

[1] J. A. Levri, D. A. Vaccari, and A. E. Drysdale, “Theory and Application of the Equivalent System Mass Metric,” in *Proceedings of the 30th International Conference on Environmental Systems*, 2000.

[2] M. Czupalla, “The Virtual Habitat - Integral Modeling and Dynamic Simulation of Life Support Systems,” Dissertation, Institute of Astronautics, Technische Universität München (TUM), Munich, 2012.

[3] P. Plötner, M. S. Anderson, M. Czupalla, M. K. Ewert, C. M. Roth, and A. Zhukov, “Status of the Correlation Process of the V-HAB Simulation with Ground Tests and ISS Telemetry Data,” in *Proceedings of the 43rd International Conference on Environmental Systems*, 2013.

[4] P. B. Hager, U. Walter, C. J. Massina, and D. M. Klaus, “Characterizing a Transient Heat Flux Envelope for Lunar-Surface Spacesuit Thermal Control Applications,” (da), *Journal of Spacecraft and Rockets*, pp. 1–10, 2015.

[5] P. B. Hager, “Dynamic thermal modeling for moving objects on the Moon,” Dissertation, Institute of Astronautics, Technische Universität München (TUM), Munich, 2013.

[6] D. W. Hensley, A. E. Mark, J. R. Abella, G. M. Netscher, E. H. Wissler, and K. R. Diller, “50 years of computer simulation of the human thermoregulatory system,” (eng), *J Biomech Eng*, vol. 135, no. 2, p. 21006, 23445051, 2013.

[7] H. Jones and J. Cavazzoni, “Top-Level Crop Models for Advanced Life Support Analysis,” in *Proceedings of the 30th International Conference on Environmental Systems*, 2000.

[8] H. Jones, J. Cavazzoni, and P. Keas, “Crop Models for Varying Environmental Conditions,” in *Proceedings of the 32nd International Conference on Evironmental Systems*, 2002.

[9] A. Stölzle, “veCROP - Development of a Dynamic Plant Model for the Use in Biological Life Support Simulations,” Diploma Thesis, Institute of Astronautics, Technische Universität München (TUM), Munich, 2014.

[10] G. Basta, “Dynamic Simulation of a Life Support System Architecture for an Asteroid Mission in VHAB,” Master Thesis, Institute of Astronautics, Technische Universität München (TUM), München, 2014.

[11] B. W. Portner, “Numerical Modeling of a Fixed Bed Adsorber for Carbon Dioxide Removal in Human Space Flight,” Bachelor's Thesis, Institute of Astronautics, Technische Universität München (TUM), Munich, 2013.

[12] D. Pütz, “Development of a Numerical Solver for Compressible Liquids,” Term Paper, Institute of Astronautics, Technische Universität München (TUM), München, 2014.

[13] M. Koppermann, “Dynamic Simulation of Water Recycling Technologies of the ISS for the V-HAB LSS Simulation,” Term Paper, Institute of Astronautics, Technische Universität München (TUM), Munich, 2011.

[14] T. Bickel, “Development of Dynamic Physico Chemical Sub-System Models for Verification and Optimization of Life Support Systems,” Diploma Thesis, Institute of Astronautics, Technische Universität München (TUM), Munich, 2009.

[15] S. Friedl, “Modellieren des ISS Lebenserhaltungssystems in der V-HAB Simulationsumgebung,” Bachelor's Thesis, Institute of Astronautics, Technische Universität München (TUM), Munich, 2014.

[16] P. Plötner, “Modeling of the ISS in V-HAB and Correlation with Flight and Ground Tests Data,” Diploma Thesis, Institute of Astronautics, Technische Universität München (TUM), Munich, 2012.

[17] C. M. Roth, “ISS Active Thermal Control System Dynamic Modeling,” Diploma Thesis, Institute of Astronautics, Technische Universität München (TUM), Munich, 2012.

[18] F. Wiesmann, “Dynamic Simulation of experimental Waste Processing Technologies for the ISS for the V-HAB LSS Simulation,” Term Paper, Institute of Astronautics, Technische Universität München (TUM), Munich, 2011.

[19] D. Williams, J. Dake, and G. Gentry, “International Space Station Environmental Control and Life Support System Status for the Prior Year: 2010 - 2011,” in *Proceedings of the 42nd International Conference on Environmental Systems*, 2012.

[20] S. Yates and R. Kay, “High Capacity Adsorbent Development for Carbon Dioxide Removal System Efficiency Improvements,” in *Proceedings of the AIAA SPACE 2010 Conference & Exposition*, 2010.

[21] Wieland, Paul, O, “Living Together in Space: The Design and Operation of the Life Support Systems on the *International Space Station,”* Marshall Space Flight Center (MSFC), Huntsville, Alabama, USA, NASA TM 1998-206956, Jan. 1998.

[22] D. Samplatsky, K. Grohs, M. Edeen, J. Crusan, and R. Burkey, “Development and Integration of the Flight Sabatier Assembly on the ISS,” in *Proceedings of the 41st International Conference on Environmental Systems*, 2011.

[23] Schaezler, Ryan, N. and Cook, Anthony, J, “Report on ISS O2 Production, Gas Supply & Partial Pressure Management,” in *Proceedings of the 45th International Conference on Environmental Systems*, 2015.

[24] R. L. Carrasquillo, D. Cloud, and R. Kundrotas, “Status of the Node 3 Regenerative ECLSS Water Recovery and Oxygen Generation Systems,” in *Proceedings of the 34th International Conference on Environmental Systems*, 2004.

[25] M. Czupalla, A. Zhukov, J. Schnaitmann, C. T. Olthoff, M. Deiml, P. Plötner, and U. Walter, “The Virtual Habitat – A tool for dynamic life support system simulations,” (en), *Advances in Space Research*, vol. 55, no. 11, pp. 2683–2707, 2015.

[26] A. Zhukov, M. Czupalla, T. Stuffler, M. Knifka, and P. Plötner, “Status of the correlation process of the V-HAB simulation with ANITA ISS data,” in *Proceedings of the 41st International Conference on Environmental Systems*, 2011.

[27] “Life Support Baseline Values and Assumptions Document,” Johnson Space Center (JSC), Houston, Texas, Mar. 2015.