Development of a Water Recovery System Resource Tracking Model

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A simulation model has been developed to track water resources in an exploration vehicle using Regenerative Life Support (RLS) systems. The Resource Tracking Model (RTM) integrates the functions of all the vehicle components that significantly affect the processing and recovery of water during simulated missions. The approach used in developing the RTM enables its use as part of a complete vehicle simulation for real-time mission studies. Performance data for the components in the RTM are focused on water processing. The data provided to the model have been based on the most recent information available regarding the technology of the component. This paper will describe the process of defining the RLS system to be modeled, the way the modeling environment was selected, and how the model has been implemented. Results showing how the RLS components exchange water are provided in a test case.

Nomenclature

AES = Advanced Exploration Systems
ALSSAT = Advanced Life Support Sizing Analysis Tool
ARS = Air Revitalization System
ARV = Asteroid Return Vehicle
BRIC = Brine Residual in Containment
BSTA = Brine Storage Tank Assembly
CDRA = Carbon Dioxide Removal Assembly
CDS = Cascade Distillation System
CFR = Carbon Formation Reactor
CH₄ = Methane
CHX = Condensing Heat Exchanger
CO₂ = carbon dioxide
CPU = Central Processing Unit
DSTA = Distillate Storage Tank Assembly
DTO = Detailed Test Objective
EAM = Exploration Augmentation Module
EC = Crew and Thermal Systems Division of NASA Johnson Space Center
ECLSS = Environmental Control and Life Support System
ER = Automation and Robotics Division of NASA Johnson Space Center
EVA = Extravehicular Activity
FOST = Forward Osmosis Secondary Treatment

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I. Introduction

Most exploration mission and habitat designs take advantage of the mass savings and efficiency of operations that a Regenerative Life Support (RLS) system will provide. The interaction between RLS subsystems involves many interdependencies both within and between subsystems. An integrated model of the architecture and the interconnections of components was needed to understand such interdependencies in a vehicle using a RLS. The Resource Tracking Model (RTM) was developed to model an integrated RLS to provide the capability of tracking the need, use, and regeneration of resources in an exploration vehicle during a simulated mission.

The capability to track the water resources during operation of a vehicle is needed to ensure that plans for an exploration mission provide adequate resources for the crew to accomplish mission objectives. The exchanges of resources between subsystems need to be coordinated so that adequate resources for one process are available when needed in another process.

Since the detailed design of the life support system for future exploration vehicles is not yet defined; RTM developers used their knowledge and documentation of technology development efforts, combined with vehicle design and mission operations that make sense for an exploration mission.

The RTM is viewed as the next step toward integrating technologies into an exploration vehicle because it starts to consider implementation of technologies into a functional system and starts the consideration of operational plans. It uses performance information from technology testing combined with sizing of reservoirs and an operational approach for the sequential operation of RLS equipment. The RTM was developed to be a tool for assessing the interactions between RLS technologies that can lead to better planning of mission operations.
The compliment of technologies in the RTM is intended to include the most likely technologies for a vehicle using a RLS. By including a representative set of RLS equipment, it is expected that simplifications of the ECLSS approach can easily be modeled. The RTM modeling approach allows performance information changes to be quickly made as technology maturity improves.

It is expected that the current version of the RTM will be used to study options for how to operate the RLS equipment and how changes in the mission plan will change the way the variety of systems interact. The RTM also enables changes in the compliment of RLS equipment to be made easily so that alternative architectures can be assessed.

This modeling effort was initiated in support of the NASA Advanced Exploration Systems (AES) project for study of an Exploration Augmentation Module (EAM). Development of the RTM also supports AES projects for Water Recovery Systems (WRS) and Air Revitalization Systems (ARS).

Interactions were underway during the writing of this paper with AES and ISS teams on the progress made in developing the RTM and the capabilities it offers for system simulation.

A review of similar simulation developments via review of the last 16 years of ICES papers revealed that several other simulation projects addressed integrated ECLSS simulation. Papers in 1999 (Dynamic RLS simulation from NASA ARC) and 2000 (Integrated Simulation of Synergistic ISS Systems during the conceptual design phase – U of Stuttgart) addressed integrated simulation of ISS systems. More recently NASA/Technical University of Munich efforts have resulted in the VHAB program. Those projects focused on ARS and WRS interactions whereas RTM addresses those interactions and the added functions of Waste Processing Systems (WPS). The RTM uses current performance information for ARS, WRS and WPS technologies.

Additionally the RTM offers compatibility with vehicle simulators that provides the capability to have ECLSS (via RTM) integrated with all other vehicle systems to conduct mission simulations.

II. Resource Tracking Model Features

Features of the modeling environment that were considered important and useful were:

1) Easily captured system architecture – The RTM creates connections between components based on Microsoft Visio schematics.

2) Object Oriented Programming – The RTM uses Object Oriented Programming to establish and encapsulate the performance of each component into a modular software representation. The object for each component can be exchanged with the object of a different technology or vintage of the component without having to significantly change the software representation of the entire system.

3) Establish component objects for all component types that are being considered for exploration vehicles – The RTM addresses the types of components being considered for human missions beyond LEO. This approach allows alternate architectures to be modeled by changing the schematic of the vehicle systems.

4) Easily integrated into higher level simulators – The RTM has been integrated into a vehicle functioning simulator for a deep space simulator that “crew” can fly for simulated missions.

5) Keep the level of simulation high so that the integrated functions of the RLS can be run quickly and so the RTM can be integrated into other simulations. The RTM uses performance data for technology at an inlet and outlet level but does not do analysis within a component for the physics going on within the component. This approach results in great model performance but limits off-nominal and contingency case capabilities. RTM is as capable as the performance data used to develop its components.

A. Modeling Data Sources

The RTM models the performance of a set of Environmental Control and Life Support System (ECLSS) equipment based on component operational or test data. Performance of the equipment is established based on operational data from International Space Station (ISS) or on the most current data on advanced technologies (references are given for each technology).

The RTM configuration of systems and subsystems was chosen to be representative of a regenerative ECLSS using ISS proven technologies combined with promising new technologies (i.e., technologies that have established performance data). The suite of equipment included in the initial RTM was chosen to address technologies that are expected to be considered for long-duration exploration missions. That set of equipment can be changed relatively easily for simulation of a more simplified approach to ECLSS or as new technology reaches maturity.

The RTM addresses crew functions using the Human Integrated Design Handbook (HIDH)-defined metabolic rates and processes combined with the exploration logistics database for crew needs such as food and packaging that results in trash waste products. Those data are consistent with the recently released Baseline Values and Assumptions
Crew functions include food and water intake, respiration, food waste generation, and crew metabolic waste generation. Crew metabolic rates are varied based on a schedule developed for the simulated crew that includes nominal, sleep, and exercise periods. Additionally, a daily crew toilet use schedule is assumed. Habitat Pressure Control System (PCS) (oxygen (O₂) and nitrogen (N₂) supply) and ARS (carbon dioxide (CO₂), water (H₂O), and heat removal) are defined based on ISS technologies. The O₂ generation occurs via ISS electrolysis technology.

To recover O₂ from CO₂, a Sabatier Reactor (SR) with performance based on ISS processes is assumed. Cabin Air Humidity removal is done via a Condensing Heat Exchanger (CHX) with performance defined via the ISS CHX. Cabin CO₂ removal and performance is simulated via an ISS Carbon Dioxide Removal Assembly (CDRA). Hydrogen for the SR is provided via the O₂-producing Oxygen Generation Assembly (OGA) with performance as in ISS OGA specification. Specification water electrolysis rates are used instead of ISS averages because exploration missions will not be as tightly constrained by orbital cycles that influence power use. No storage of hydrogen (H₂) is included (similar to how the ISS ECLSS functions to interact with the SR commercial Demonstration Test Objective).

Supporting functions of food processing, handling food wastes and human wastes are simulated according to operations representative of exploration missions. The amount of trash to be processed is defined in the habitation team logistics model for trash products that are expected to be generated during a long-duration Mars mission.

The function of the toilet is based on ISS toilet and operations technology to collect solid and liquid waste products, and to pretreat urine. New technologies are used for urine processing and recovery of water from cabin waste products based on promising Cascade Distillation System (CDS) and Heat Melt Compactor (HMC) technologies. Water recovery from brine is included based on the Brine Residual in Containment (BRIC) technology development. Trash that contains water is assumed to be processed by the HMC. The Water Processing Assembly (WPA) filtration and ion removal system of the ISS is assumed for producing potable water.

The RTM has capabilities to include simulation of extravehicular activity (EVA) events. However those capabilities are currently under review, and the RTM test case does not include EVA simulations. EVA systems interactions with an exploration vehicle RLS are important but not currently established. The interaction between the habitat RLS and EVA systems will be critical for exploration missions with significant EVA when EVA is addressed as an integral part of an exploration RLS.

The WRS in the ISS includes the potable water tanks, the toilet (including pretreat subsystem), a Vapor Compression Distillation (VCD) system, and the WPA. The cabin CHX provides water directly to the WPA; the CDS product water goes to the WPA. WPA product water is used for drinking, for toilet flush, and to provide water for electrolysis in the OGA.

The RTM includes the ISS functions but replaces the VCD with the CDS and adds the BRIC and HMC for the integrated exploration ECLSS. CDS distillate water goes to the WPA and Brine goes to the BRIC. BRIC water recovered is distillate, but volatiles or other impurities may be found in the BRIC distillate product. Therefore, the BRIC product water is plumbed to the CDS waste water tank to be reprocessed by the CDS. HMC product water is a distillate and feeds the WPA. Distillate water from the CHX, CDS, or HMC is thought to be pure enough to use as flush water for the toilet.

B. Functional Schematic Development

RTM development first focused on the utility of existing system information and connectivity between simulation programs. It was determined that schematics that use Visio can be used in other programs such as System Modeling Language (SysML) and the Johnson Space Center (JSC) Automation and Robotics Division (ER) developed Trick/GUNNS program to establish simulation connections.

Early in RTM development, plans were to use existing ISS ECLSS schematics as the starting point for the RTM so that all the valves, tanks, and ancillary equipment that the operational ISS system includes would be captured. However, in working with the ISS ECLSS community, NASA determined that the detail in the ISS ECLSS schematics is not available in a form that is recognizable by other programs, such as Visio.

The JSC ECLSS community used Visio to generate schematics for many systems. An integrated ECLSS schematic had just been released as part of a study of the Mars Habitat ECLSS during the same time RTM development was initiated. That schematic contained most of the ISS ECLSS components but added many advanced ECLSS technologies to more completely close the system (closure minimizes waste products and venting to the surrounding environment and minimizes mass). The Mars Habitat schematic was evaluated for technologies that could be used in the RTM, and many functions represented were common. Therefore, the Mars Habitat schematic was chosen as the starting point for generating the RTM schematic.

The RTM schematic establishes how RLS components interact with fluid/gas streams. Although many subsystem processes are addressed, the schematics do not show the many reservoirs that several subsystems employ.
The Mars Habitat ECLSS contained redundancy thought to be needed for such a mission. That redundancy was not included for the initial RTM since the basic functions could be modeled without the complexity of failure simulations that would employ redundant components. Several advanced technologies (i.e., washer/dryer, Hygiene (shower), Forward Osmosis Secondary Treatment, and Low Power CO₂ Removal) were not mature enough to include in the RTM because performance data were not available. The resulting RTM schematic, shown in Figure 2, is simplified versus the Mars Surface Habitat (SH) schematic. The Visio version of the schematic in Figure 2 was provided to JSC ER and was used to create the RTM model.

C. Resource Tracking Model Program Consideration and Synergy

Initial concepts for simulation leading to the capability to simulate the integrated ECLSS performance considered programs recently used for ECLSS evaluations such as Easy5, SysML, Advanced Life Support Sizing Analysis Tool (ALSSAT), G189A, and Thermal Desktop. The extensive infrastructure but limited fluid property capabilities of Easy5 and SysML would have made a simulation model using that program limited. The ALSSAT program has the technology functional information needed but is only designed for steady-state assessments of technology variations. SysML is capable of modeling system requirements, behavior, structure, and parametrics, but requires a separate engine for performing simulations. The G189A program has not been updated recently, thus its capabilities to simulate advanced ECLSS components would have needed to be augmented. Thermal Desktop is better suited for dominantly thermal problems. Other programs such as ASPEN, PROCESS, CHEMCAD and MathLab/Simulink address more detailed chemical processes and were viewed as better suited for individual component modeling.
A team of engineers in the JSC robotics was tasked to develop a vehicle simulation for the EAM project\textsuperscript{11} that was to include ECLSS in the vehicle simulator. Thus, a synergistic connection between the life support effort to develop a RTM and the robotics effort to develop a vehicle simulator was initiated. Life support would provide information to include in the Trick/GUNNS simulator, and Robotics would implement the performance and operational logic in the RTM for the EAM. Robotics would then operate the RTM to simulate exploration missions.

The Trick/GUNNS simulator is compatible with Visio and can take objects from Visio to develop a Trick/GUNNS model. The resulting Trick/GUNNS RTM simulator can operate separately to meet the needs of the ECLSS community for simulation of the operation of the integrated ECLSS. The RTM is also used in integrated vehicle simulations to simulate operation of the EAM in real time and is connected to displays and control system simulators to provide the capability to “fly” the EAM.

D. Details on the Trick Simulation Framework and the GUNNS Extension

Trick is a JSC standard simulation environment used for the development and operations of both analysis and real-time, human-in-the-loop, training simulations.\textsuperscript{11} A few past examples of Trick in use at JSC include simulations of the following systems: Shuttle Remote Manipulator System, Space Station Remote Manipulator System, Simplified Aid for EVA Rescue (SAFER), and recently an ISS training simulation for JSC flight controllers. The simulation applications range from laptop and desktop computer trainers to full-scale robotics hardware-in-the-loop facilities and virtual reality systems. Trick provides a data-driven real-time scheduling executive, input processing, data recording, and automatic code generation. Trick is open source and freely available at https://github.com/nasa/trick.
The RTM uses Trick primarily for its time management, thread management, and data collection mechanisms. GUNNS, a C++ Trick extension, is used as the primary solver for the RTM. The subsystems within the RTM are separated into individual Trick GUNNS networks and then placed within their own simulation modules. As an example, the ARS would exist within one module, the PCS in another, and the Sabatier Reactor in yet another simulation module. GUNNS acts as the solver for each system represented by its network of components. It uses a network definition file in order to generate a C++ class representing the system model. The GUNNS solver interprets this model as an algebraic system of equations to be solved at every time step. The network representation relies on modified nodal analysis techniques familiar to electrical circuit simulators. GUNNS extends the concept and applies it to model electrical, fluid, and thermal systems. The subsystem model, a C++ class, is instantiated within the Trick simulation definition file. The simulation definition file also specifies the update rate for every model within the simulation. Trick then schedules a set of jobs that must occur within a single simulation time step (simulation frame). At the end of a simulation frame, interface data is shared across GUNNS networks. Trick then proceeds to the next simulation frame and repeats the process.

In the case of the RTM, the fluid aspects of GUNNS were primarily used. This includes fluid properties tables, and often-used fluid system component models such as pumps, fans, valves, pipes, and tanks. Schematics of the system are converted into a GUNNS representation in order to capture the system connectivity in the model. At the present time, GUNNS comes with a Visio plug-in that allows systems to be built out of common components in a drag-and-drop fashion. After building a candidate system schematic, the Visio plug-in then parses the drawing and converts it into GUNNS and Trick-compatible C++ code automatically. Development of the RTM utilized SysML schematics of Regen-ECLSS as a source of system information when developing the GUNNS compatible Visio drawings.

In addition to real-time scheduling, Trick also allows the user to initialize all model parameters from a simulation input file. This allows for quick tweaks to be made in order to change things like mission duration, tank sizes, addition or removal of crew members from the model, and changes to the crew’s daily schedule. In many cases, system tweaks can be made and a follow-on analysis can be performed without any need to re-compile the simulation executable. Trick also has a built-in Monte Carlo framework that can allow the analyst to statistically vary important system sizing parameters and record simulation output in an automated fashion.
E. Using a Trick Simulation to Integrate the Resource Tracking Model into a Full Vehicle Simulation

At present, JSC has several vehicle simulations with the capability of placing candidate vehicle designs in a variety of space environments. Some examples of the current vehicle simulation capabilities include: Orion in a variety of transfer orbits, or Orion docked in a vehicle stack configuration; the Multi-Mission Space Exploration Vehicle on the surface of an asteroid, or the surface of a Mars moon; the EAM participating in the Asteroid Retrieval Mission with Orion and the ARV. All of these simulations are built on top of the Trick simulation framework, and they employ a variety of Trick extensions to model orbital dynamics, vehicle guidance, navigation, and control, propulsion, and contact physics, to name a few. The simulations also use JSC’s Dynamic Onboard Ubiquitous Graphics and Engineering Dynamic Onboard Ubiquitous Graphics for Exploration packages along with hardware input devices to create an immersive three-dimensional simulation experience for users to “fly” these vehicles (see Figure 3).

The RTM represents a potential RLS for deep space manned vehicles. It makes sense to evaluate this model in the context of a simulated space vehicle environment. The selection of Trick and GUNNS as the basis for the RTM has made integration with JSC’s existing deep space vehicle simulations a much easier process. At present, JSC is working on a simulation that places an Orion, EAM, and ARV within an LDRO (Lunar Distant Retrograde Orbit). This simulation will incorporate the work done on the RTM as part of the EAM’s RLS. It will combine this system with GUNNS models of EAM’s proposed Electrical Power System and Thermal Control System. All of these systems have
simulated interfaces between each other and to the external spacecraft environment. The goal of the effort is to give systems engineers a view of how candidate system designs perform in an integrated mission. As an example, it could give insight into how slight orbital maneuvers might be made in order to avoid eclipses within a LDRO in order to make power available to the RLS components. If power cannot always be made available to the RLS, it will have an impact on how the RLS is actually operated during the mission. In addition, the RLS has large electrical power loads. Representative power loads throughout a mission can be generated from the integrated vehicle simulation and provided to power system designers. Ideally, the integrated models will provide additional insight into vehicle performance that may not be available from more stand-alone models.

III. Environmental Control and Life Support System Performance Information and Mission Operations

The RTM has simulated the integrated functions of an advanced regenerative ECLSS for an exploration mission scenario. This required establishing a mission timeline that includes the general functions of the crew, and the operation of each of the regenerative ECLSS components.

The broad collection of vehicle systems integrated together in the RTM mission simulator, had to be address how to initialize the mission. Questions such as: How large should the tanks be?; What is to be assumed to be loaded in tanks to start a mission?; What should drive the sequence of operations of the variety of components?; How detailed does the simulation of each component have to be to assure interactions with other components is relatively accurate?; and What mission scenario should be used to demonstrate and test the RTM?

A briefing to the WRS team in early summer of 2014 provided information on how the RTM project was evolving. The team was engaged to establish how the integrated system should function. Many questions were addressed via the resulting interaction. However, other questions crossed team boundaries. Operational details were not well established for many component interactions. The strong interaction between technology developers and the Mission Operations Directorate teams will occur later for exploration systems. Interactions with the ISS ECLSS community resolved more questions on how ISS systems were operated.

One outcome of the interactions was the finding that the regenerative EAM ECLSS will be similar in functions and thus will require subsystems that will be similar to the sizes used on the ISS. Therefore, many tanks have used ISS tank sizes as a starting point for the EAM ECLSS.

However, ISS ECLSS operations are different, in many ways, than those envisioned for the EAM. The ISS has backup in Russian elements that an EAM is not likely to have. The EAM will probably include a higher degree of ECLSS “closure” than the ISS achieves because the EAM must function much more independently. Regenerating more waste products via the HMC and the BRIC will lead to a higher-percent recovery of waste water. The operation of the SR in EAM will be an integral part of the balance of consumables, and that balance will be much more important for independently operating exploration habitats.

A. Additional Information Needed for an Integrated Regenerative Life Support Vehicle Simulation

A detailed operational timeline for equipment use during an exploration mission has not been developed. The RTM developers had to develop operational logic and initial design information to simulate mission operations of the RLS. The added information includes:

1) Timeline of crew activities
2) Tank sizes for a variety of tanks
3) Routing of fluids between tanks and components
4) Sequencing of equipment operations
5) Interdependencies of component operations
6) Operation that provides the force to move fluids through the systems

The number of crew envisioned for many exploration missions is similar to the number of crew that ISS equipment is designed to support. The length of independent operations for exploration missions means that reserves must address longer nominal and contingency operations. Therefore, the tank sizes of the ISS were used both for commonality with existing proven equipment and to be representative for a vehicle designed for exploration. The initial RTM runs assume the crew size is four; thus ISS tanks designed for 6 to 8 crew should be adequately sized.

The metabolic rates, supporting food and water supplies and consumable goods, trash generated and the portion of that trash that can be used in the HMC were all sized for a crew of four. The nominal use of such supplies and the resulting metabolic products were defined based on the June 2014 HIDH.\footnote{Source: Integrated Human Information Database (HIDH).}
A basic day of operations was defined to test the RTM. Simulating a basic crew day provides insights into the normal exchange of fluids (and gases) that will take place during an exploration mission. The basic day shown in Figure 5 establishes the crew routines for daily activities including: sleep, nominal activities, exercise, use of the commode (Rest Room (RR)), consumption of food and drinks (H2O), and generation of trash. The HIDH combined with the Logistics Database was used to calculate values related to crew activities. A representative timeline of activities was developed for the crew to time processes (Figure 5). The timeline shown starts with crew wakeup at 0.0 hours.

![Nominal Crew Morning Schedule](image)

![Nominal Crew Afternoon Schedule](image)

**Figure 5. The crew timeline of activities for a nominal day of exploration operations.**

B. Logic for operating the commode, Cascade Distillation System and Brine Residual in Containment

The logic developed for use of the commode (RR in Figure 5) started with the crew use timing shown in Figure 5. For each commode use, the RTM assumes that the ISS-derived system will operate a fan/separator to provide the suction to draw urine, flush water, and pre-treat chemicals through a system that feeds the CDS Waste (water) Storage Tank Assembly (WSTA). That flow is assumed to be processed by a Urine Processing Assembly (UPA) Precipitation Prevention Project (PPP) Ion Exchange (IX) Column (UPIX) prior to it going to the CDS WSTA to remove excessive calcium. When the CDS WSTA quantity exceeds its limit, it is assumed to be full and CDS operations are initiated. CDS operations continue until the waste water tank quantity lower limit is reached, then the CDS is deactivated. Each CDS operation results in the inlet pretreated urine being pulled through a UPIX to remove excess minerals. Distillate is routed into a Distillate Storage Tank Assembly (DSTA) and brine created during that operation is placed in the CDS Brine Storage Tank Assembly (BSTA). When the DSTA level reaches its upper limit, the DSTA is emptied into the WPA Waste Water Tank Assembly (WWTA). When the BSTA exceeds a full limit, the BSTA connection to the BRIC is opened and the brine is processed to recover water, which is routed to the WSTA to be reprocessed via the CDS. The CDS provides the pumping needed to move distillate and brine via pitot forces.

Solid waste products from the commode and the BRIC are tracked by the RTM as waste products that are stored as solid waste.

1. **Logic for Heat Melt Compactor Operations**

The HMC operations are also defined related to crew operations. The logistics model of products used and waste generated defines the variety of waste products that result from crew activities. HMC developers target a subset of the solid and liquid waste products produced by the crew for processing by the HMC. Testing has established that the representative mix of waste products that the HMC can process will have some water, and HMC operations can recover a portion of that water in the form of distillate. The crew activity timeline establishes that, after breakfast each day, a crew will load the HMC with material that it can process. Then, the HMC will be activated and will spend much of the day processing that waste into a stabilized block of waste and distilled water. The distilled water is pumped to the WPA WWTA by the water separator included in the HMC.
2. Logic for Water Processor Assembly Operation

The WPA is assumed to be off until the WWTA orbital replacement unit reaches a full state (assumed to be 95% full). The WPA is then operated to purify distillate until the WWTA reaches empty (5%). Potable water is plumbed to WSTAs. Three WSTAs are assumed for the RTM so that water quality can be verified before it is used and to provide water for potential contingencies. The RTM assumptions for operation of three WSTAs is that Tanks 1 and 2 will start full and Tank 3 should start at 70% full so that one tank can receive WPA water. Water is to be used from WSTA 1 until it reaches empty (assumed to be 5% full), then valving is switched so that water is used from WSTA 2. When WSTA 2 is near empty, plumbing is changed to draw water from WSTA 3, which should be filled by the WPA by that time.

3. Air Revitalization System Processes that Affect the Exploration Augmentation Module Water Balance

ARS components that affect the water balance are the CHX, which condenses water from the cabin atmosphere, the PCS that requires water to produce O₂ (via electrolysis) for storage and crew use, the CDRA, which removes CO₂ from the cabin and provides CO₂ (to recover O₂) via a SR, which combines CO₂ and H₂ to create water and Methane (CH₄). Water from the SR is assumed to be pure and thus compatible with the potable water supply; therefore, the water is sent to the WSTAs. CH₄ is vented in this version of the RTM.

Humidity and CO₂ generated by the crew are varied based on metabolic rates associated with crew activities such as nominal, exercise, and sleep. Thus the amount removed varies during each day to keep humidity and CO₂ within limits.

The CHX is operated in the RTM by assuming that humidity in the cabin is removed at the rate it is generated in the cabin (assuming the Thermal Control System is working nominally). The simplification may be replaced with more detailed CHX modeling in future releases of the RTM. The water separator not only separates condensate from air, it pumps CHX-collected water to the WPA WWTA.

CDRA operations are assumed to be nominal for collecting CO₂ from cabin air and thus maintaining CO₂ partial pressure within limits. As CO₂ is added to the cabin by the crew, it is removed by the CDRA and is sent to a CO₂ storage tank via a compressor. Compressed CO₂ is sent to the SR when the CO₂ tank reaches an upper limit and O₂ is being generated by the OGA. Since no storage of H₂ is currently assumed in the RTM (as in the ISS), H₂ is vented if there is no CO₂ for the SR to use. Likewise, if the CO₂ tank is full and no electrolysis is needed, then excess CO₂ would be vented. To size the CO₂ tank, the RTM used logic that used nominal crew operations to predict the O₂ use rate and thus the time at which O₂ would need to be generated; the RTM then estimated the amount of CO₂ that the CDRA would provide and sized the CO₂ collection tank so that it could reach its upper limit near the time that O₂ generation is required.

O₂ and N₂ tank sizing is based on ISS sizing (15.2 ft³ with maximum pressure of 2740 psia). OGA, CDRA, and SR design and performance is based on ISS technology and operations (except that ISS restrictions related to sun/shade changes are not used for the EAM).

Operations of the ARS/PCS system use logic that starts SR operations after the CO₂ tank is full (reaches 95%) and O₂ makeup is required. Operations continue to use CO₂ and H₂ to provide water until the CO₂ tank is empty (assumed to be 5%). If the CO₂ tank is full but no O₂ generation is required, CO₂ is vented until O₂ generation is required. If O₂ generation is required but no CO₂ is available, H₂ would be vented.

C. Test Mission Definition

A target mission was developed, since detailed mission operations plans are not established for exploration missions and are needed to test the RTM capabilities. To test the RTM, a nominal EAM mission lasting 60 days of operations starting with crew arrival and occupation of the DSH was assumed. The crew timeline of water and food consumption, exercise, trash, and metabolic waste generation (shown in Figure 5) was assumed. Tanks and provisions were loaded as anticipated for the start of a deep space mission. The EAM was assumed to provide all crew support for nominal activities.

Crew metabolic functions are defined via HIDH data shown in Table 1 and via the timeline of nominal crew activities that describes when the crew would drink, eat, exercise, use the commode (Figure 5), and load the HMC with trash. The waste water tanks are filled and the potable water tanks are depleted based on those nominal daily and weekly activities.

Automation of the rest of the RLS functions is assumed as related to the fill of tanks and the depletion of water and O₂ resources. The RTM simulation provides the quantities in each consumable container as a function of time related to the metabolic rates and the operation of the RLS equipment.
D. Water Processing Components of the Regenerative Life Support

The HMC operation has been simulated based on top-level estimates of the amount of waste that the HMC can process and the amount of water contained in that waste. The portion of water reclaimed by the HMC via evaporation then condensation is based on the HMC performance data from testing. Table 2 summarizes the HMC operations assumed including the timing of operations. The HMC planning is that a crew member will load the HMC with the compatible trash after the early meal. The crew will activate the HMC, and the HMC will process the trash over the next 17.5 hours. The HMC products will be removed the next day and a new batch of trash will be loaded to begin the next batch. Much of the HMC data are based on the logistics database. Water removed from trash by the HMC is separated from the air stream via a separator that also provides the pumping power to move the condensate to the WPA WSTA. 

Table 2 summarizes the HMC operations assumed including the timing of operations. The HMC planning is that a crew member will load the HMC with the compatible trash after the early meal. The crew will activate the HMC, and the HMC will process the trash over the next 17.5 hours. The HMC products will be removed the next day and a new batch of trash will be loaded to begin the next batch. Much of the HMC data are based on the logistics database. Water removed from trash by the HMC is separated from the air stream via a separator that also provides the pumping power to move the condensate to the WPA WSTA.

E. Water Recovery System Operations

The Commode (or Waste and Hygiene Compartment (WHC)) performance is based on ISS WHC performance data. The ISS WHC mixes urine with 50 ml of condensate water (potable water on ISS) and 3 mL of pretreat for each use. Each use is estimated to take around 10 minutes during which time the fan/separator is operating (it is assumed to operate for 20 minutes when used during defecations).

UPIX performance is simulated using the simplification that the UPIX removes around 0.5% of the urine/flush/pretreat/brine condensate flow. Removing calcium before CDS processes increases the capability of the CDS to recover a higher percentage of water from the waste stream. Performance of the CDS is based on test data from 2014. Operation of the CDS is started when the CDS WSTA reaches 95% full and continues until the WSTA reaches 5%.

BRIC operation performance is based on BRIC testing documented in Ref. 8. The BRIC can recover 86% of the water in brine; however, that water is expected to have some level of volatiles that makes it useful to return it to the CDS instead of directly to the WPA. BRIC operations are started when the CDS BSTA reaches 90% full and stopped when the BSTA quantity reaches 5%. Solids removed by the BRIC are stored in solid waste storage. WPA operation is based on ISS WPA performance as simplified by removing a percentage of the inlet waste water stream. The WPA is operated when the WWTA is filled to above 80% and is stopped when the WWTA quantity reaches 5%.

Tank capacities have been based on ISS tank sizes as in Table 3 below. Storage tanks associated with urine and HMC condensate and CHX condensate storage were determined not to be needed based on interactions with the WRS team. Instead, flow of those streams is plumbed directly to tanks in the CDS or WPA. Those tanks can also receive flows while providing fluid to be processed simultaneously. Tank sizes for the variety of ARS and PCS tanks are based on ISS tanks sizes, as shown in table 3.
Table 2. Heat Melt Compactor Assumptions and Parameters

<table>
<thead>
<tr>
<th>Parameters for the HMC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average power during operation = 429 W</td>
<td></td>
</tr>
<tr>
<td>1.01 kg/crew/day of trash is produced and 35% is water = 0.35 kg/crew/day</td>
<td></td>
</tr>
<tr>
<td>Assume 80% recovery of water in the HMC wastes = 0.28 kg/crew/day</td>
<td></td>
</tr>
<tr>
<td>Average the recovery over the operational time of the HMC</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assume crew loads the HMC then operation is automated</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start loading at the end of the post sleep period (hour 3)</td>
<td></td>
</tr>
<tr>
<td>Loading takes around 20 minutes per day</td>
<td></td>
</tr>
<tr>
<td>Operate one time per day start at hour 3.5</td>
<td></td>
</tr>
<tr>
<td>Takes around 17.5 hours to process one batch</td>
<td></td>
</tr>
<tr>
<td>At a later time (long enough to complete operation including cool down) the crew unloads the HMC and reloads with a new batch of trash</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water evaporation and subsequent condensation is automated</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All condensed water is assumed to be near the quality of the UPA (CDS) distillate</td>
<td></td>
</tr>
<tr>
<td>HMC water is flowed to the WPA waste water tank.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solid Waste Storage capacity is assumed to be large enough for entire mission’s trash</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trash accumulated at a set rate.</td>
<td></td>
</tr>
<tr>
<td>HMC processes a portion of this trash for water extraction. The rest of the trash is returned to storage.</td>
<td></td>
</tr>
</tbody>
</table>

F. Air Processing Components of the Regenerative Life Support

The CHX performance is simplified to remove humidity at the rate it is input into the cabin. The CHX water separator operation provides the pumping power to send CHX condensate to the WPA.

OGA operation is based on ISS OGA capabilities as defined in the OGA Specification. Rates are based on the specified requirement of providing 12 lb/day of O₂. However, the use rate for the EAM is based on the specification rate without adjustment for orbital sun/shadow periods that constrain ISS OGA operations. The continuous OGA operation results in a water use rate of 0.9 lb/hr. The OGA is to operate when the O₂ tank providing O₂ to the cabin reaches 50%. It continues to operate until the O₂ tank reaches 95% full. The OGA draws water from the potable water tanks. The H₂ produced is used by the SR to recover water or vented overboard if the SR is not operating.

Cabin CO₂ is removed by technology such as the ISS CDRA. A simplifying assumption is that CO₂ is collected at the rate it enters the cabin. Collected CO₂ is compressed into a storage tank for use in the SR. The SR is operated when CO₂ stored is available, and the OGA is operated to provide H₂. If the CO₂ tank is full but OGA operation is not required excess CO₂ is vented overboard.
Table 3. Capacities and Initial Fill of the WRS and PCS Tanks

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Function</th>
<th>Acronym</th>
<th>Capacity (LB)</th>
<th>Starting % Full</th>
<th>Starting mass (KG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRS</td>
<td>WPA</td>
<td>Waste Water Tank</td>
<td>WWTA</td>
<td>125</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potable water tanks</td>
<td>WSTA1</td>
<td>125</td>
<td>95</td>
<td>118.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WSTA2</td>
<td>125</td>
<td>95</td>
<td>118.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WSTA3</td>
<td>125</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pretreat tank</td>
<td></td>
<td>5</td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>CDS</td>
<td></td>
<td>Waste Storage</td>
<td>WSTA</td>
<td>32.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brine Storage</td>
<td>BSTA</td>
<td>32.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distillate Storage</td>
<td>DSTA</td>
<td>32.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solid Waste</td>
<td>HMC</td>
<td></td>
<td>No storage only recovery of water and compaction of waste products</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Function</th>
<th>Acronym</th>
<th>Capacity (ft³)</th>
<th>Starting % Full</th>
<th>Starting mass (LB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Control System</td>
<td>Gas storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>O2 Tanks</td>
<td></td>
<td>Tank 1</td>
<td>15.2</td>
<td>95</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tank 2</td>
<td>15.2</td>
<td>95</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>N2 Tanks</td>
<td></td>
<td>Tank 1</td>
<td>15.2</td>
<td>95</td>
<td>42.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tank 2</td>
<td>15.2</td>
<td>95</td>
<td>42.7</td>
</tr>
</tbody>
</table>

SR performance is based on testing\textsuperscript{18}. The SR has been modeled in some detail in the RTM. CH\textsubscript{4} produced by the SR is vented overboard. Water is separated from SR products by a separator that also provides the pumping of the water to the WPA WSTAs. The SR simulation in Trick/GUNNS is shown in Figure 6.

Figure 6. The model representation of the SR.
IV. Test Case Results

With the RTM model configured with 1) information to define the RLS system modeled, 2) the mission data for a nominal day of operations and 3) the component performance data; a test case was defined. Early runs focused on ensuring the logic was being accurately used during a nominal week of operation of an EAM. That set of runs was used to confirm that operations were as intended. Many things were learned during those runs that resulted in refinement of the logic to operate components and size tanks.

Once nominal operations were established; it became obvious that long runs were needed to visualize the operation of the RLS. Using ISS tank sizes for the O₂ and the compliment of 4 crew results in the O₂ tank not reaching its 50% full limit for over 30 days. Thus only after that long did the OGA get activated to provide O₂ to refill the tank, and H₂ needed to run the Sabatier reactor. Full EAM mission length runs of 60 days were then run to demonstrate the full range of operations of RLS equipment and thus the interactions between the RLS equipment. This test run should not be considered an EAM mission simulation because the details of an EAM mission were not available to be included.

Results that follow are from the 60 day mission simulation. Since this test case was intended to demonstrate the RTM capabilities, only nominal operations were assumed and EVA was not included.

The cabin conditions are captured in Figure 7. The variations associated with the day (nominal and exercise) metabolic rates and sleep periods are obvious with the daily cycles. The CO₂ pressure is controlled in a narrow band and the CO₂ removed varies a little with the metabolic rates as shown in the last plot of Figure 7. The collection of CO₂ contributes to the calculation of a CO₂ storage tank size (that accommodates the nominal CO₂ generated for the period it takes to deplete the O₂ storage tank to its lower limit).

Figure 8 captures the simulation of the interconnection of the O₂ and CO₂ tanks in the first of the plots. That shows that the CO₂ tank sizing did produce the desired results as it shows the O₂ tank is depleted to its lower limit as the CO₂ tank becomes full at 13 hours. However subsequent cycles show that the need for O₂ and the production of CO₂ are not well matched since O₂ generation is not required when the CO₂ tank is filled again. The logic used says that when the O₂ is no longer required the SR must stop operations. However, when the CO₂ tank reaches full again O₂ is still not needed; therefore excess CO₂ is vented until O₂ is needed again.

The operation of the SR is best shown in the upper right plot of figure 8. Mass balance for the SR (upper right) and SPE operations (lower left) can be seen in these plots for the periods each subsystem is operated (the H₂ plus CO₂ are equal to the H₂O out plus the CH₄ out).

The overall use of O₂, water in the SPE and water produced via the SR operations are shown in the last plot along with the period wherein CO₂ is vented (25 to 35 hours).

![Figure 7. RTM 60 day mission. HAB Pressure, Temperature, PPCO₂, and CO₂ Removal Rate.](image-url)
Figure 8. RTM 60 day mission. O$_2$ and CO$_2$ tank quantities, SR flows, and SPE flows.

The operation of the WHC area is reflected in tank quantities in Figure 9. For each cycle the CDS WSTA fills and then CDS operations flow distilled water to the WPA WSTA over a relatively short period. Also shown is the slower accumulation of brine in the Brine tank. When the brine tank reaches full, operation of the BRIC is started resulting in flow into the CDS WSTA. BRIC operation is reflected in the much longer cycles that show that only two periods of operation of the BRIC are required during 60 days of nominal crew operations.

The lower plots of Figure 9 show the quantity variations of the 3 potable water tanks. The logic used draws potable water from a single tank until the quantity reaches the lower limit of 5%. Following that event, the model automatically switches to use the next available tank. WPA produced water is directed to flow into a tank that has available capacity. In the event all three tanks are full, the WPA water is flowed into an overflow tank in order for the model to keep track of the excess water production. This trend can be observed in the second plot in Figure 9. The variations change significantly when the SPE (OGA) and SR operations are drawing water from tanks and adding water back to the tanks during SR operations (25 to 45 hours).

The operation of the HMC is reflected in the profiles of Figure 10. Flow of water is averaged over the operational period of the HMC, as illustrated in the mass flow during each day of HMC operation. The sawtooth form of solid tank waste mass reflects the transient operation wherein trash (acceptable to the HMC) is taken from the trash mass (downward change) processed in the HMC, then the solid part of the HMC is returned to solid waste storage (upward change).

Figure 11 shows the CDS, CHX and HMC quantities of water produced during the EAM mission contribute to the total of over 1000 kg of water that is reclaimed. The upper right plot shows the relative contribution of the SR and WPA to the total of around 1050 kg with over 100 kg of water produced by the SR.

When those quantities are compared to the potable water used by the crew and by the SPE for electrolysis (shown in the lower left plot) an excess of water (the lower right plot) is predicted of around 220 kg. The excess is a result of the water content in food and the HMC trash processing that is not removed via the PWD. Those added sources of water are greater than the mass of water lost in other products such as fecal matter or cabin atmosphere leakage or inefficiencies in the BRIC or trash water removal.
Figure 9. RTM 60 day mission. Waste and potable water tank quantities.

Figure 10. RTM 60 day mission. Trash accumulation and HMC distillate production.
Water processing subsystem functions are reflected in the quantities shown in Figure 11.

Figure 11. Waste and potable water production/consumption, and excess potable water production.

Figure 12. Total potable water. Sum of all three potable water tank quantities.

The potable water quantity resulting from the integrated processes is shown in Figure 12 to be relatively constant when the integrated processes are taken into account.
A. Mass Balance of Water and Oxygen during Operation of the Exploration Augmentation Module

Viewing the balance of H$_2$O for the vehicle requires considering all the potential H$_2$O processes because water will shift from one process to another during the operation of the vehicle. Additionally, the crew use of H$_2$O has to consider several factors including drinking H$_2$O, H$_2$O consumed via food and water in trash products that is recovered. Movement of H$_2$O around the vehicle will depend on operation of 1) H$_2$O collection in the commode via urine, 2) condensate in the CHX and 3) the HMC. Additionally, H$_2$O used in the OGA to create O$_2$ and H$_2$O produced via the SR will move resources. Automated controls driven by logic for how to operate the equipment will determine when each of the recovery components operates based on tank quantities and related processes. That movement of water and related resources has been illustrated in the RTM plots for the simulated EAM length mission just presented.

The RTM calculates where the inventory of H$_2$O is at any time and illustrates how the H$_2$O resource flows from the variety of components and storage tanks during the operation of the vehicle.

A set of logic has been developed to check the mass balance based on the performance of the variety of components included in the RTM. The logic is implemented in a Microsoft Excel spreadsheet that uses component performance data to calculate the flow through each component and how much of the resource is used or created during operation of the component. To check the mass balance, the spreadsheet tracks the flows through each component based on the length of time the component is operated. The time the component is operated is determined by the Trick/GUNNS RTM based on the mission scenario and the resulting timing of operation of each component. Alternatively, the mass balance spreadsheet can be run by assuming the time of operation of each RLS component or simply by assuming the length of mission.

In a RLS, each of the subsystems balances inputs and outputs during the time it is operating. For example; Figure 8 that shows the SR and SPE inlets balance the outlets. The same balance is achieved for each of the RTM components.

The spreadsheet version of such checks shows that during this 60 day mission the SPE (OGA) constrains SR use to 21.5 days when the OGS is providing H$_2$ for SR use. During that 21.5 days of combined SR and OGS use; the SR uses 23.4 kg of H$_2$ and 148 kg of CO$_2$ (sum = 171.4 kg) while it produces 96.3 kg of water and 75.2 kg of CH$_4$ (sum = 171.5 kg).

A vehicle mass balance must assess the inlets into the RLS and the outlets from the RLS. The products entering the RLS are food, trash (that is processed by the HMC) and urine pretreat. The products that exit an RLS are unused trash, stored feces, brine solids, vented gases (CH$_4$ from the SR); CO$_2$ (from CO$_2$ storage); H$_2$ (from SPE)) and atmosphere that is leaked from the cabin.

Many processes affect food that is consumed by the crew to convert it to CO$_2$, and feces and water (respiration, urine and sweat). The products are dissimilar, thus a direct comparison between inputs and outputs is complicated.

The mass balance spreadsheet considers all inputs and outputs to calculate the balance. The summary page of the Mass Balance spreadsheet is shown in Table 4. The summary is arranged to focus on water related processes (as the focus of the RTM) and not on vehicle mass balance.

Data from the summary shows that 374 kg of food is consumed, HMC related trash input is 242 kg and negligible pretreat (1.4 kg) or 617 kg of RLS inputs. Out of the RLS 174 kg of trash is sent to storage from the HMC, 92 kg of waste solids (fecal matter, solids in urine and BRIC solids); 130 kg of gases are either vented or leaked for a total stored or vented of 396 kg. The difference of 221 kg is stored as 49 kg of CO$_2$ in the tank; 147 kg increase in potable water and 25 kg of waste water in tanks to be processed.

Near the bottom of the summary, the calculations show that for the compliment of equipment included in the RTM, (for the water that is useable in the vehicle) there is a net increase of 147.3 kg of H$_2$O to the potable water system. That increase is partially accounted for by recognizing that water from the HMC trash collected and water in the food consumed is not drawn from the potable water system.

The right hand side of Table 4 provides insights into the total quantities that are stored as waste products or are vented as either waste or excess. Of the processes assumed for the RTM around 130 kg of products are vented waste or leaked products.
### Table 4. Mass Balance Spreadsheet Results for a 60 day EAM Length Mission

<table>
<thead>
<tr>
<th>Resource Tracking Model Mass Balance</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Duration =</td>
<td>60.00</td>
<td>Days</td>
</tr>
<tr>
<td>Number of crew =</td>
<td>4.00</td>
<td>#</td>
</tr>
<tr>
<td><strong>Crew related masses</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2O consumed (Drink+Hydration of food + Hygiene)</td>
<td>696.00</td>
<td>kg</td>
</tr>
<tr>
<td>Food consumed</td>
<td>374.40</td>
<td>kg</td>
</tr>
<tr>
<td>Water in food</td>
<td>172.80</td>
<td>kg</td>
</tr>
<tr>
<td>Total H2O consumed</td>
<td>868.80</td>
<td>kg</td>
</tr>
<tr>
<td>O2 Consumed</td>
<td>196.80</td>
<td>kg</td>
</tr>
<tr>
<td>CO2 Produced</td>
<td>249.60</td>
<td>kg</td>
</tr>
<tr>
<td>Urine produced</td>
<td>407.04</td>
<td>kg</td>
</tr>
<tr>
<td>Feces produced</td>
<td>72.00</td>
<td>kg</td>
</tr>
<tr>
<td>Water in Feces</td>
<td>24.00</td>
<td>kg</td>
</tr>
<tr>
<td><strong>ARS via CHX, OGA, CDRA, SR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net H2O Used</td>
<td>115.10</td>
<td>kg</td>
</tr>
<tr>
<td>Net O2 Produced</td>
<td>187.91</td>
<td>kg</td>
</tr>
<tr>
<td>Net CO2 Used</td>
<td>147.98</td>
<td>kg</td>
</tr>
<tr>
<td>Net H2 Vented</td>
<td>0.00</td>
<td>kg</td>
</tr>
<tr>
<td>SR CH4 Vented</td>
<td>75.17</td>
<td>kg</td>
</tr>
<tr>
<td>CO2 Stored at the End of the Mission</td>
<td>49.59</td>
<td>kg</td>
</tr>
<tr>
<td>CO2 Vented during the Mission</td>
<td>52.03</td>
<td>kg</td>
</tr>
<tr>
<td><strong>WRS processes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDS Distillate produced</td>
<td>446.52</td>
<td>kg</td>
</tr>
<tr>
<td>HMC Distillate produced</td>
<td>67.87</td>
<td>kg</td>
</tr>
<tr>
<td>Condensing HK Distillate produced</td>
<td>444.00</td>
<td>kg</td>
</tr>
<tr>
<td>Total distillate to WPA</td>
<td>958.40</td>
<td>kg</td>
</tr>
<tr>
<td>Total Potable water produced</td>
<td>958.40</td>
<td>kg</td>
</tr>
<tr>
<td>Total Water Consumed</td>
<td>936.67</td>
<td>kg</td>
</tr>
<tr>
<td>Total Water Recovered</td>
<td>843.30</td>
<td>kg</td>
</tr>
<tr>
<td>Total water stored at mission start</td>
<td>153.41</td>
<td>kg</td>
</tr>
<tr>
<td>Total water used from potable storage</td>
<td>811.10</td>
<td>kg</td>
</tr>
<tr>
<td>Total water to potable storage</td>
<td>958.40</td>
<td>kg</td>
</tr>
<tr>
<td>Change in H2O in Potable storage</td>
<td>147.30</td>
<td>kg</td>
</tr>
<tr>
<td>Potable water remaining at mission end</td>
<td>300.71</td>
<td>kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waste products to storage</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Matter</td>
<td>72.00</td>
<td>kg</td>
</tr>
<tr>
<td>H2O in fecal matter</td>
<td>24.00</td>
<td>L (or kg) of water</td>
</tr>
<tr>
<td>Solids in Urine</td>
<td>15.84</td>
<td>L of solids</td>
</tr>
<tr>
<td>BRIC solids</td>
<td>4.42</td>
<td>kg of solids</td>
</tr>
<tr>
<td>Total H2O related products to storage</td>
<td>52.26</td>
<td>kg</td>
</tr>
<tr>
<td><strong>Lost or vented consumables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cabin Leakage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constituent Mass Leaked N2</td>
<td>2.40</td>
<td>kg</td>
</tr>
<tr>
<td>O2</td>
<td>0.74</td>
<td>kg</td>
</tr>
<tr>
<td>H2O</td>
<td>0.04</td>
<td>kg</td>
</tr>
<tr>
<td>CO2</td>
<td>0.00</td>
<td>kg</td>
</tr>
<tr>
<td>Total</td>
<td>3.18</td>
<td>kg</td>
</tr>
<tr>
<td>Net H2 vented</td>
<td>0.00</td>
<td>kg</td>
</tr>
<tr>
<td>CO2 Vented during the Mission</td>
<td>52.03</td>
<td>kg</td>
</tr>
<tr>
<td>SR CH4 Vented</td>
<td>75.17</td>
<td>kg</td>
</tr>
<tr>
<td>Total Lost/Vented products related to H2O</td>
<td>130.38</td>
<td>kg</td>
</tr>
</tbody>
</table>

Other pages of the mass balance spreadsheet address:
1. Mission parameters – to define the mission in length, the compliment of equipment used, reservoir sizes
2. Crew data – all the functions relating to crew consumption and production of resources,
3. ARS processes – ARS functions related to water balance, PCS, CHX, SPE, SR operations
4. WRS processes – processes that provide potable water and those that recover H2O
5. Atmospheric Leakage – to calculate how much of each constituent is lost
6. HMC parameters – to establish quantities of waste that are processed to recover H2O
Some of the factors that will result in mass loss from the RLS of a vehicle, even if the RLS the RTM simulates regenerates most resources:

1) Water will be lost in feces – the RTM assumes that feces is collected and not processed to recover water.
2) Solids will be removed at a variety of points in the system and those will include a small amount of water.
   a. The BRIC will remove a high percentage of the water in urine, but the residual solids will have some water and will be waste products.
   b. The UPIX will remove mainly calcium, but that small portion of the urine flow will be lost in the
      UPIX when it is replaced.
   c. The WPA will filter out a number of water impurities – when the WPA filters are replaced the filtered
      solids will be lost.
   d. The HMC will not recover 100% of the water in waste that it processes. The solids and residual water
      are lost as solid HMC products. Other solid waste products that are not processed in the HMC result
      in lost consumables.
3) Cabin atmosphere loss due to leakage – very small leak rates are allowed but that will result in loss of N₂, O₂, 
   H₂O, and CO₂.
4) SR venting of CH₄ – the SR process, included in the RTM, will vent CH₄ (other RLS technologies may recover
   some of that resource).
5) H₂ and CO₂ venting when tanks are full, but scenarios don’t allow use of those resources (for example when
   electrolysis is not required to replenish O₂ but CO₂ is not available when electrolysis is operating. Loss of H₂
   or CO₂ could be minimized by adding a H₂ storage tank so that H₂ is available when CO₂ is also available).
6) Residual H₂O may be included in vented CH₄ or vented H₂ or vented CO₂ – separation processes are not
   100% effective in separating water from other gases.
7) During EVAs, consumables will be lost during a variety of processes depending on the technology used. The
   amount will depend on the technology options used and how frequently EVAs are conducted. Those processes
   will be added to the RTM in future developments.
   a. Processes to cool the suit and to remove H₂O and CO₂ may result in loss of those consumables.
   b. Waste products produced during EVAs may result in other consumables being lost (e.g., products such
      as the Maximum Absorbency Garments).

However, the use of a RLS minimizes the loss of consumables. Loss of consumables must be addressed via
provisions taken on exploration missions. Food, H₂O, O₂, N₂, and many other consumables will be provided at
the start of each mission. The amount will be determined based on crew size, mission length, and technologies used in
exploration vehicles. Simulation of missions using RTM will help in establishing the amount of each resource that
must be provided to carry out each mission. Steady-state assessments with programs such as ALLSAT will also aid
in establishing the total of each consumable that will be needed.

The RTM provides estimates of where the major resources are within a vehicle using RLS. That information
enables mission planners to monitor the fill state of the variety of systems in the vehicle to assess the overall operation
of the vehicle. Thus, the balance of the processes employed by the vehicle can be monitored. The RTM test mission
results in the simulation of consumables reflected in Figure 12. The mass balance of the integrated operation of the
RLS components of the EAM is illustrated, and shows that the flows of water in and out of components and the crew is essentially balanced even though the logic of operations shifts the water resource from
one part of the vehicle to another over the week of nominal operations.

V. Overview and Conclusions

The development of a simulation for tracking water resources involved establishing a likely compliment of components for a regenerative life support system for an exploration vehicle. During the course of establishing the content of such a system many attributes for the components were established based on ISS and advanced technology performance information. To develop the RTM and simulate operations of an exploration vehicle required:

1) Developing a schematic of an exploration vehicle RLS and a way to automate modeling based on Visio schematics
2) Refining a habitat model to address anticipated crew metabolic processes, to include food use, and to include
   trash generation and processing
3) Modeling of each of the RLS components via data from the ISS or advanced (but mature) new technologies
   (much of which has been defined via data from recent ICES papers)
4) Sizing the variety of tanks needed to store and then providing for processing of H₂O, CO₂, O₂, and N₂
5) Defining a day of vehicle operations that defines how crew interact with the vehicle RLS
6) Including the logic for operating RLS components

RTM modeling efforts have provided a tool to model the transient operation of a vehicle using a regenerative life support system. The model is expected to be the basis for trade studies that vary equipment connections and missions to be simulated.

The RTM has been integrated into the vehicle simulation of an Exploration Augmentation Module that is being used for EAM mission studies as integrated with other vehicle systems.

To demonstrate the RTM capabilities, operations have been simulated to show how the integration of components will process water (as connected) to address expected, nominal crew operations for a 60 day EAM mission. Results of that simulation provided insights into the interaction of RLS components and visualization of the transfer of resources between subsystems.

The Trick/GUNNS simulation environment has addressed the modeling of RLS equipment based on performance data of each component. Trick/GUNNS allows inclusion of more detailed component models if deemed relevant and as information becomes available.

In concert with the RTM a mass balance checking spreadsheet was developed. That spreadsheet was developed to check RTM predictions. The spreadsheet is also useable in a standalone model to predict resources needed for the RLS that RTM addresses.

VI. Future Plans

The RTM was established as a tool that can be used to simulate the transient operation of a vehicle using RLS technologies. It can be used to simulate mission scenarios using exploration vehicles employing RLS technologies to conserve limited resources.

The simulation of 60 days of nominal EAM habitat operations provided an example of the RTM capabilities. Future operation of the RTM is expected to address different mission operations to simulate a more complete exploration mission.

The RTM was designed to allow object-oriented exchange of data so that component descriptive data can be easily exchanged to allow simulation of alternative vehicle architectures. It is expected that system architectures envisioned for future exploration vehicles will consider other technologies and processes. RTM modeling in Trick/GUNNS will allow other architectures to be created by object-oriented programming exchange of component data.

Interaction with the technology development community for ECLSS, WRS, and logistics will lead to refinement of the data used and potentially the architecture of the system that is modeled in the RTM. Interaction with the EAM project will lead to variations of the system architecture to be simulated and the missions to be addressed in future simulations of the RTM.

Evolution of the EVA simulation included in the RTM will lead to simulation capabilities for mission scenarios involving EVAs. Interaction with technology developers and mission planners will lead to refinement of the RTM mission operations.

The RTM provided a transient simulation capability of an exploration vehicle integrated regenerative life support system. It is the most recent model to integrate ARS and WRS functions and might be the first to integrate WMS functions with ARS and WRS. It will be used for the variety of simulation needs that technology developers and mission planners develop for exploration missions.

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