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Resource Tracking Model Updates and Trade Studies

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The Resource Tracking Model has been updated to capture system manager and project manager inputs. Both the Trick/General Use Nodal Network Solver Resource Tracking Model (RTM) simulator and the RTM mass balance spreadsheet have been revised to address inputs from system managers and to refine the way mass balance is illustrated. The revisions to the RTM included the addition of a Plasma Pyrolysis Assembly (PPA) to recover hydrogen from Sabatier Reactor methane, which was vented in the prior version of the RTM. The effect of the PPA on the overall balance of resources in an exploration vehicle is illustrated in the increased recycle of vehicle oxygen. Case studies have been run to show the relative effect of performance changes on vehicle resources.

Nomenclature

ARS = Air Revitalization System
BPA = Brine Processing Assembly
BRIC - Brine Residual in Containment
BSTA = Brine Storage Tank Assembly
CDRA = Carbon Dioxide Removal Assembly
CDS = Cascade Distillation System
CH_4 = methane
CHX = Condensing Heat Exchanger
CO_2 = carbon dioxide
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
GUNNS = General Use Nodal Network Solver
HAB = Habitation
HIDH = Human Integrated Design Handbook
HMC = Heat Melt Compactor
HyPA = Hydrogen Purification Assembly
H_2 = hydrogen
H_2O = water
ISS = International Space Station
JSC = Johnson Space Center
N_2 = nitrogen
OGA = Oxygen Generation Assembly
OGS = Oxygen Generation System

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O_2 = oxygen
PCS = Pressure Control System
psia = pounds per square inch absolute
PPA = Plasma Pyrolysis Assembly
$PPCO_2$ = partial pressure of carbon dioxide
PPO_2 = partial pressure of oxygen
RLS = Regenerative Life Support
RR = Rest Room
RTM = Resource Tracking Model (for Regenerative Life Support)
SPE = Solid Polymer Electrolyzer
SR = Sabatier Reactor
SysML = System Modeling Language
TCCS = Trace Contaminant Control System
UPA = Urine Processing Assembly
Visio = a diagramming and vector graphics application; part of the Microsoft Office family
WHC = Waste and Hygiene Compartment
WPA = Water Processor Assembly
WPS = Waste Processing System
WRS = Water Recovery System
WSTA = Water Storage Tank Assembly
WTA = Waste Tank Assembly (of the UPA)
WWTA = Waste Water Tank Assembly (of the WPA)

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) (documented in the 2015 ICES paper[1]) 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 (H_2O) 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 summer of 2015, the RTM has been refined in several key ways to add capabilities and to more closely match evolving plans for exploration vehicles. The major areas that have been refined are: 1) the way components interface with one another (reflected in the edited schematic) to reflect the exploration Environmental Control and Life Support System (ECLSS) team plans for ECLSS (as documented in an AIAA Space 2015 paper[2]); 2) the operation of the Oxygen Generation Assembly (OGA) (to continuously provide oxygen (O_2) to match crew metabolic use); 3) carbon dioxide (CO_2) collection systems to continuously collect CO_2 and provide the CO_2 needed to match the hydrogen (H_2) provided to the Sabatier Reactor (SR); 4) SR operations to operate at a ratio that reacts all CO_2 entering the SR; 5) the addition of new simulations of equipment that will process methane (CH_4) generated by the SR to recover and reuse the H_2 in the CH_4 (the Plasma Pyrolysis Assembly (PPA))[3] to break down the waste stream of gases from the SR and the Hydrogen Purification Assembly (HyPA)[4] to separate the H_2 from the PPA stream and make it available to be used in the SR. Interesting findings on the PPA and HyPA integration are provided in a trade study.

In order to completely simulate the processes that affect resource use during exploration life support use, the processes that use resources during Extravehicular Activities (EVA) have to be included. Simulation of the EVA systems addresses the need for O_2, H_2O, and nitrogen (N_2) and for the processing of other consumables such as wipes. Subsystems that conserve cabin and/or airlock air during depress operations will affect the resources needed and thus need to be included. To address the EVA simulation need, meetings with the exploration EVA community are planned to ensure that RTM simulations of EVA processes are in concert with exploration planning. The RTM includes a simplified EVA airlock and cabin resources simulation. The EVA simulation will be added to a future version of the RTM.

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 initiates the consideration of operational plans. It uses performance information from technology testing combined with the 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.

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 in which 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. Several trade studies have been conducted with the RTM to illustrate how the model can be used to assess the resources required when different operational scenarios or different technology performance is employed.

This modeling effort was initiated in support of the NASA Advanced Exploration Systems project for study of an Exploration Augmentation Module (EAM).

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 RTM include easily captured system architecture, Object Oriented Programming, easy integration into higher-level simulators, and the ability to keep the level of simulation high so that the integrated functions of the RLS can be run quickly and the RTM can be integrated into other simulations.

A. Modeling Data Sources

The RTM models the performance of a set of ECLSS equipment based on component operational or test data. Performance of the equipment is established based on operational data from the International Space Station (ISS) or on the most current data on advanced technologies.

A SR with performance based on ISS processes is assumed to recover O_2 from CO_2. Cabin air humidity removal is done via a Condensing Heat Exchanger (CHX), with performance defined via the ISS CHX. Cabin CO_2 removal and performance is simulated via an ISS Carbon Dioxide Removal Assembly (CDRA). H_2 for the SR is provided via the O_2-producing OGA, with performance as in ISS OGA specification.[5] The ISS approach to operating the OGA assumes that the OGA is started when the cabin pressure requires O_2, and operates continuously thereafter at a rate that matches the Pressure Control System (PCS) needs for O_2. O_2 is introduced directly into the cabin from the OGA. The resulting H_2 is provided to the SR at a low rate. No storage of H_2 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[6] 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 simulated for urine processing and recovery of water from cabin waste products based on promising Cascade Distillation System (CDS) [7] and Heat Melt Compactor (HMC) [8] technologies. Water recovery from brine is included based on the Brine Residual in Containment (BRIC) [9] technology development. Each of those components is viewed as a generic capability to distill urine, recover water from brine, and recover water from habitation wastes; however, the specific performance of those components is based on the CDS, BRIC, and HMC technologies. 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.

Interaction with system managers for ECLSS led to changes in the RTM simulation presented in the 2015 ICES paper to reflect the system architecture planned by exploration ECLSS managers.[2] That system configuration is shown in Figure 1.

Figure 1 also includes new components for technologies that completed demonstration testing during the fall of 2015. Those address recovery of H_2 from the CH_4 produced in the SR to improve the recovery of the O_2 from the CO_2 that the crew produces. A PPA and a HyPA are modeled to simulate recovery of H_2, which is then used in the SR to supplement the H_2 from the OGA and thus enable reacting more of the CO_2 produced to recover more of the O_2.

The RTM simulates crew functions using the Human Integrated Design Handbook[10] (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. Interaction with NASA Johnson Space Center (JSC) experts resolved a small mass imbalance when using Human Systems Integration Requirements data directly. That led to understanding that the

HIDH-required food is not equal to the food that the crew consumes – a portion of that food is discarded with packaging and a portion is not wanted by a crew member (i.e., he or she doesn't eat the full portion).

Condensate water is provided directly to the WPA from the CDS, BRIC, HMC, and SR. SR water was thought to be very pure and thus compatible with the potable water supply system; however, system managers pointed out that the SR product water will have a significant gas content and will not be treated with biocide. The SR water is routed to the inlet of the WPA for processing to address those concerns. WPA product water is used for drinking and toilet flush, and to provide water for electrolysis in the OGA (as is done on ISS currently).

B. Functional Schematic Development

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. Redundancy was not included in the RTM since the basic functions could be modeled without the complexity of failure simulations that would employ redundant components.

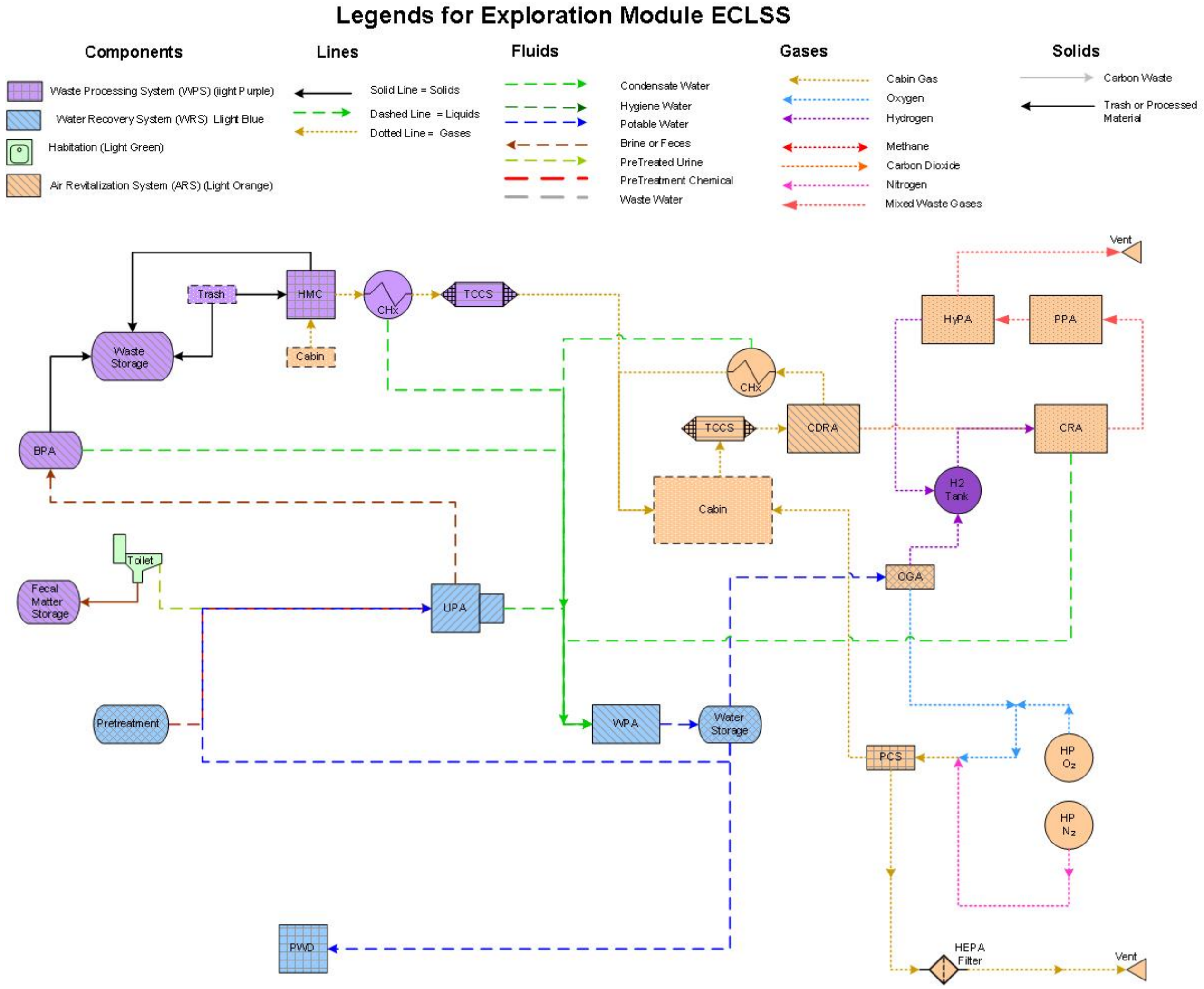


Figure 1. Integrated RLS used in the RTM.

Life support provided information to include in the Trick/General Use Nodal Network Solver (GUNNS) simulator. The NASA JSC robotics team implemented the performance and operational logic in the RTM to operate the RTM to simulate exploration missions.

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 (as illustrated in Figure

2). 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 that is open source and freely available at https://github.com/nasa/trick.

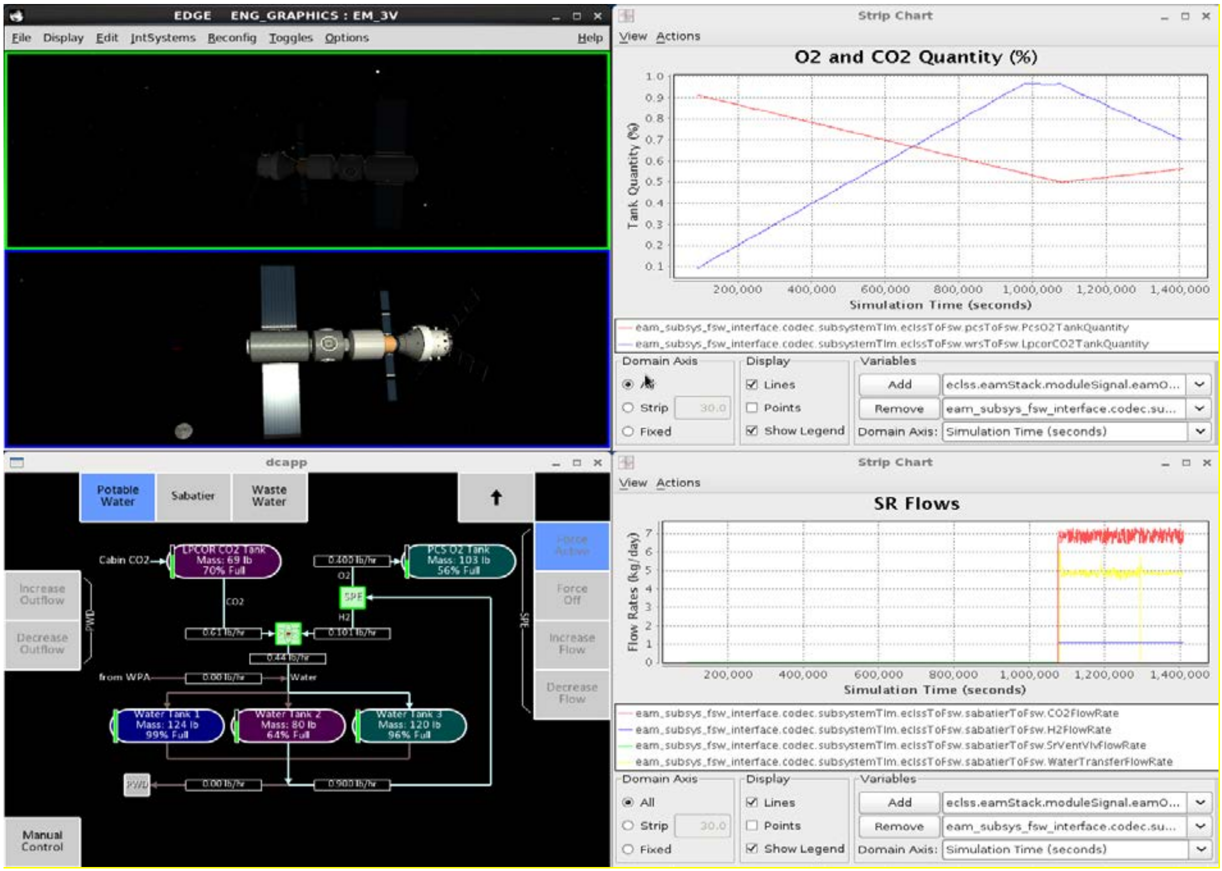


Figure 2. Displays and controls for RTM when run within an integrated deep space vehicle simulation.

In the case of the RTM, the fluid aspects of GUNNS were primarily used. This included fluid properties tables and often-used fluid system component models such as pumps, fans, valves, pipes, and tanks. Development of the RTM utilized System Modeling Language (SysML) schematics of Regen-ECLSS as a source of system information when developing the GUNNS-compatible Visio drawings.

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 test scenario consisted of crew activities and equipment operations envisioned for a nominal 60 days of a deep space mission, and was the scenario that was discussed in the 2015 ICES paper.[1]

A basic day of operations was defined to test the RTM. A simulation provides insights into the normal exchange of fluids (and gases) that will take place during an exploration mission. The basic day shown in Figure 3 establishes the crew routines for daily activities including: sleep, nominal activities, exercise, and use of the commode (Rest Room (RR)), consumption of food and drinks (H_2O), and generation of trash. 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.

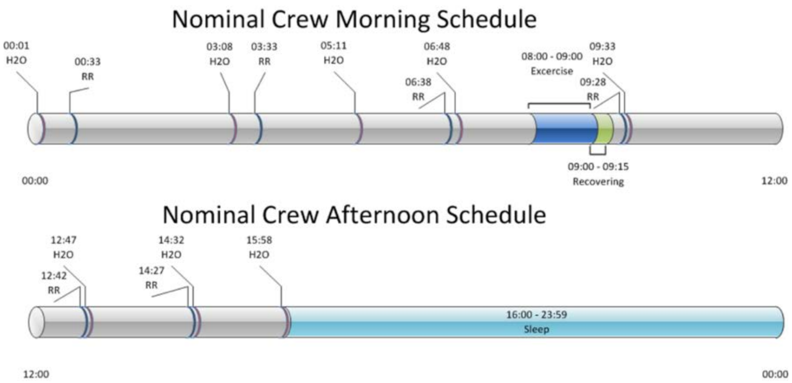


Figure 3. The crew timeline of activities for a basic day of exploration operations.

A. Logic for Operating the Exploration Vehicle Regenerative Life Support

All the operations involving the RLS of an exploration vehicle are included in the way the water, waste, air, and human logistics are sequenced during each of the 60 simulated days.

1. Logic for Heat Melt Compactor Operations

The logic for the HMC recognizes that compatible wastes will be processed over a 22 hour period. After that time the crew will unload the HMC and reload it with accumulated trash, and will start the process again.

2. Logic for Operating the Commode, Urine Processing Assembly and Brine Processing Assembly

The timing of the operation of the commode is based on the crew timeline. Each use results in a mixture of urine, urine pretreat, and flush water being pumped via an air/fluid separator to flow into the Urine Processing Assembly (UPA) waste tank assembly. The UPA is operated when the Water Tank Assembly (WTA) reaches a fill level and is stopped when an empty level is reached. Performance data for the UPA are based on testing of the CDS technology.

Brine is pumped to the Brine Processing Assembly (BPA) tank via pitot pumping in the UPA. The BPA is operated when the brine tank reaches a set fill level and continues over a long period to process all the brine. Performance data for the BPA are based on the BRIC technology. Other brine processing technologies are in work. The performance data from those technologies are expected to be used in future RTM simulations.

Distillate is pumped to the WPA Waste Water Tank Assembly (WWTA) during BPA operations. This routing is different than in the 2015 RTM paper[1] reflecting the system manager input that the distillate from the BPA will be compatible with the quality needed for the WPA.

3. Logic for Water Processor Assembly Operation

Operation of the WPA is the same as in the 2015 RTM paper.[1] Operation of the potable water tanks is sequenced to provide one receiving tank, one supply tank, and another that is in reserve. If the tanks are completely filled, additional water storage is assumed to be available and the amount of water stored in other tanks is tracked.

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

Air Revitalization System (ARS) components that affect the water balance include: the CHX, which condenses water from the cabin atmosphere; the PCS that requires water to produce O_2 (via electrolysis); the CDRA, which removes CO_2 from the cabin and provides CO_2 (to recover O_2) for use in the SR, which combines CO_2 and H_2 to create water and CH_4.

CH_4 was vented in the prior version of the RTM but is now processed by the PPA[3] and HyPA[4] to recover H_2 for reuse in the SR. Simulation of the operation of the SR now includes use of the H_2 from the HyPA in addition to the OGA-produced H_2. To simulate the functions of the OGA, SR, PPA, and HyPA, the constituent flows of H_2, CO_2, hydrocarbons, and H_2O had to be addressed and included because those constituents affect the operating efficiency of those processors. An assumption for the goal of SR operations was made for the molar ratio of CO_2 to H_2 to simulate the mix of constituent gases. That molar ratio was used to calculate the efficiency of the SR processor and predict the resulting outlet flows from the SR. The condensed liquid water is pumped to the WPA WWTA via the liquid/gas separator of the SR.

Outlet gas constituents are routed to the PPA. Moderate temperature cooling was assumed for the SR, which led to the dew point temperature of the SR outlet gases. PPA efficiency was used to simulate PPA processing of the combined CH_4, H_2O, unreacted H_2, and unreacted CO_2. Products of the PPA were simulated based on performance curves provided in the 2015 ICES paper on development of the PPA.[3] The PPA products were then processed by the HyPA and, based on Fall 2015 testing of the HyPA,[4] an 85% recovery rate of H_2 in that stream was achieved for the

HyPA stream. The HyPA will probably process for a period of time to accumulate H_2, and will be regenerated by thermally releasing the H_2. An average rate of H_2 recovery will be used as a simplification of the recovery process in the RTM simulation. The recovered H_2 will supplement the H_2 produced by the OGA to increase the rate of H_2 and CO_2 reaction in the SR, thereby increasing the recovery of O_2 from the CO_2 generated by the crew. Other gases in the HyPA stream are to be vented to space and are thus lost from the vehicle RLS.

At present, the RTM does not include a H_2 storage tank to accumulate H_2 from the OGA and HyPA. The need for such a device may be established via RTM simulations.

The CHX and CDRA are operated in the RTM to maintain cabin humidity and keep partial pressure of carbon dioxide (PPCO_2) below 2.0 millimeters of mercury. The water separator not only separates condensate from air, it pumps CHX-collected water to the WPA WWTA. The rate of humidity and CO2 removal vary based on crew metabolic rates and the assumption that the thermal control system will provide adequate cooling to operate the CHX.

CDRA operations are assumed to be nominal for collecting CO_2 from cabin air, thus maintaining CO_2 partial pressure within limits. As CO_2 is added to the cabin by the crew, it is removed by the CDRA and is sent to a CO_2 storage tank via a compressor. Compressed CO_2 is sent to the SR when O_2 is being generated by the OGA. The CO_2 tank has been sized to be an ISS standard 50 kg capacity tank.

If the CO_2 tank is full but SR operation is required, CO_2 is vented until O_2 generation is required. If O_2 generation is required but no CO_2 is available, H_2 would be vented if the H_2 tank is full.

B. Test Mission Definition

To test the RTM, a nominal EAM mission lasting 60 days of operations was assumed, starting with crew arrival and occupation of the DSH. That period is adequate to establish the nominal operation of RLS equipment and cycling of RLS processes. The crew timeline of water and food consumption, exercise, trash, and metabolic waste generation (shown in Figure 5) was assumed.

Crew metabolic functions are defined via HIDH[10] 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 3), and load the HMC with trash. The per crew information in Table 1 is used to calculate the crew metabolic inputs into the cabin considering the number of crew and a daily timeline of crew activities. The waste water tanks are filled and the potable water tanks are depleted based on those nominal daily and weekly activities (Table 2). That data establishes the capacity and initial loading of each of the tanks so that simulations can be initialized and the logic to address how to operate the tanks results in realistic system operations.

Automation of the rest of the RLS functions is assumed as related to the fill of tanks and the depletion of water and O_2 resources. The RTM simulation calculates the quantities in each consumable container as a function of time related to the metabolic rates and the operation of the RLS equipment.

C. 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.[7] HMC water is pumped to the WPA WWTA.

1. Water Recovery System (WRS) 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).

Use of the new pretreat for urine is assumed, thereby resulting in no need for the Urine Processing Assembly Precipitation Prevention Project Ion Exchange Column (included in the 2015 RTM paper[1]).

D. Air Processing Components of the Regenerative Life Support

The cabin pressure control relies on N_2 from the PCS system, when required, and uses PCS O_2 only for contingencies in which the OGA is not available. The OGA operations are assumed to start with crew ingress at 0 hours and continues at a rate approximately equal to crew consumption of O_2 to maintain cabin partial pressure of oxygen (PPO_2). OGA operation is simulated to introduce O_2 directly into the cabin, and H_2 goes directly to the SR.

Table 1. Crew Metabolic Rates (from HIDH)

Parameter	Rate	Breakdown	Units
Consumption Rate H2O	2.9		kg/crew/day
		2	kg/crew/day drinking
		0.5	kg/crew/day for food rehydration
		0.4	kg/crew/day for hygiene
Production Rate H2O Vapor	1.85		kg/crew/day
Production Average Rate Urine	1.696		kg/crew/day
		1.63	L of water/crew/day
		0.066	L of solids/crew/day
Fecal matter average	150		grams (by mass)
Average two defecations per day	2		
		150	mL (by volume) /crew/defecation
Feces will have an average		100	ml of water /crew/day (50 ml /crew/defecation)
Consumption Rate O2	0.82		kg/crew/day
Production Rate CO2	1.04		kg/crew/day
Total food required	1.83		kg/crew/day
Food Consumed		1.5189	kg/crew/day
Food not consumed (rejected or waste)		0.3111	kg/crew/day
Water in food consumed		0.701	kg/crew/day

Table 2. Capacities and Initial Fill of the WRS and PCS Tanks

Subsystem	Component	Function	Acronym	Capacity		Starting	Starting mass	
				LB	KG	% Full	LB	KG
WRS	WPA	Waste Water Tank						
			WWTA	125	56.81	0	0	0
		Potable water tanks						
			WSTA1	125	56.81	95	118.75	53.97
			WSTA2	125	56.81	95	118.75	53.97
			WSTA3	125	56.81	80	100	45.45
	Pretreat tank	Pretreat Urine		5	L			
	CDS	Waste Storage						
			WSTA	32.3	14.7	0	0	0
		Brine Storage						
			BSTA	32.3	14.7	0	0	0
		Distillate Storage						
			DSTA	32.3	14.7	0	0	0
Solid Waste	HMC	No storage only recovery of water and compaction of waste products						
				Capacity		Starting	Starting mass	
Pressure Control System		Gas storage		ft3	KG	% Full	LB	KG
	O2 Tanks		Tank 1	15.2	83.2	95	37.4	78.19
			Tank 2	15.2	83.2	95	37.4	78.19
	N2 Tanks		Tank 1	15.2	94	95	42.7	94
			Tank 2	15.2	94	95	42.7	94

The H_2 flow into the SR from the OGA is limited to that produced when O_2 is supplied to the cabin at metabolic rates. Thus, there are two factors limiting the operation of the SR: the H_2 supply rate, and the CO_2 supply rate. The H_2 flow rate limits the amount of H_2 that can be used to react with the CO_2 in the SR. The new approach to recovering the O_2 from cabin CO_2 involves recycling the H_2 by processing the SR outlet stream of gases to separate the H_2 from compounds and return the recovered H_2 to the SR. The recirculated H_2 enables reacting more of the CO_2 and thus recovery of more O_2.

SR operations are very efficient when the molecular ratio of H_2 to CO_2 is 4.5:1. The simulation of SR operations that uses the 4.5:1 ratio results in a waste gas stream that contains no residual CO_2. However, the waste gas stream will contain unreacted H_2 and residual water in addition to the CH_4.

Dr. Jeff Sweterlitsch/NASA JSC was consulted and provided insights that were essential in translating the chemistry of molecular ratios into the kg/hr flows used in the RTM. Assumptions used were a crew of four for rates of CO_2 generation and O_2 consumption; a moderate temperature (65°F (18°C)) cooling used in the SR CHX (to calculate the condensation rates and predict the amount of residual H_2O in the SR outlet gas stream). Those calculations are shown below:

Assumptions:

1) Flow rate of H_2 entering the Sabatier is 1.09 kg/day (based on a crew of four and the O_2 flow needed to match metabolic use of O_2)
2) Chemical reaction assumes 4.5 moles of H_2 per mole of CO_2 with no excess CO_2 in CH_4 stream
3) Occurs at ambient (101325 Pa)
4) 18°C (65°F) dew point of H_2O = 2126.8 Pa pp H_2O (Sweterlitsch's equation)

$$\frac{1.09\,\frac{kg\ H_2}{day}}{0.002\,\frac{kg\ H_2}{mol\ H_2}} = 545\ \frac{mol\ H_2}{day}\ supplied$$

$$\frac{1\ mol\ CO_2}{4.5\ mol\ H_2} \times 545\ \frac{mol\ H_2}{day} = 121.1\frac{mol\ CO_2}{day}\ supplied$$

$$121.1\frac{mol\ CO_2}{day} \times 0.044\frac{kg\ CO_2}{mol\ CO_2} = 5.33\ \frac{kg\ CO_2}{day}\ supplied$$

$$\frac{2\ mol\ H_2O}{1\ mol\ CO_2} \times 121.111\frac{mol\ CO_2}{day} = 242.2\frac{mol\ H_2O}{day}\ generated$$

$$242.2\frac{mol\ H_2O}{day} \times 0.018\frac{kg\ H_2O}{mol\ H_2O} = 4.36\ \frac{kg\ H_2O}{day}\ generated$$

$$\frac{2}{1+2+0.5} = 0.571\ \frac{mol\ H_2O}{mol\ products}$$

$$0.571\frac{mol\ H_2O}{mol\ products} \times 101325\ Pa = ppH_2O = 57900\ Pa$$

$$\frac{57900\ Pa - 2126.8\ Pa}{57900\ Pa} = 96.3\%\ H_2O\ condensed$$

$$4.36\ \frac{kg\ H_2O}{day} \times 96.3\%\ H_2O\ condensed = 4.20\ \frac{kg\ H_2O}{day}\ condensed$$

$$\frac{1\ mol\ CH_4}{1\ mol\ CO_2} \times 121.1\frac{mol\ CO_2}{day} = 121.1\frac{mol\ CH_4}{day}\ generated$$

$$121.1\ \frac{mol\ CH_4}{day} \times 0.016\frac{kg\ CH_4}{mol\ CH_4} = 1.94\ \frac{kg\ CH_4}{day}\ generated$$

$$\frac{0.5\ mol\ H_2}{4.5\ mol\ H_2} \times 1.09\frac{kg\ H_2}{day} = 0.12\ \frac{kg\ H_2}{day}\ unreacted\ in\ methane\ stream$$

$$4.36\frac{kg\ H_2O}{day} \times (100\% - 96.3\%)\ H_2O\ uncondensed = 0.16\ \frac{kg\ H_2O}{day}\ in\ methane\ stream$$

Overall mass balance:

$$5.33\ \frac{kg\ CO_2}{day} + 1.09\frac{kg\ H_2}{day} = 1.94\frac{kg\ CH_4}{day} + 4.20\frac{kg\ liquid\ H_2O}{day} + 0.16\frac{kg\ vapor\ H_2O}{day} + 0.12\frac{kg\ H_2}{day}$$

In testing of the PPA[3] it was found that the performance of the PPA is affected significantly by the amount of gases other than CH_4 in the outlet SR gas stream. Dr. Morgan Abney reported on PPA development results in 2015[3] and provided results for a pure CH_4 stream and a stream from a SR that is most representative of expected exploration vehicle operations. The results of that study have been used to simulate the operation of a PPA unit with a crew of four. The outlet conditions of the PPA are calculated using the SR constituent gas flow and molecular ratios to simulate PPA performance. Only the CH_4 is expected to be reacted in the PPA, thus the other gases in the SR stream are simulated as passing through the PPA unreacted. Downstream, the gas stream will contain unreacted CH_4, the H_2 resulting from the PPA reaction of CH_4, the H_2 and H_2O in the inlet stream.

The HyPA processes that stream and, based on testing done in the fall of 2015[4], will recover 85% of the H_2 in that stream. The HyPA will recover H_2 by absorbing the H_2 from the gas stream, then desorbing it during a regeneration process. For the RTM simulation, the recovery of the HyPA-absorbed H_2 will be simulated as a continuous process. In reality, the desorption process will be performed over a short duration. That process is approximated via the RTM through the continuous flow of H_2. The need to have a process that provides somewhat continuous H_2 flow may force the inclusion of a H_2 storage tank.

The goal of the PPA and HyPA recovery of H_2 is to increase the amount of CO_2 that can be reacted and thus increase the O_2 recovery rate. However, a balance is not assured since the H_2 flow rate is restricted by the OGA need to provide O_2 at metabolic rates, and the CO_2 is available at the rates generated by the crew. If an imbalance results in more CO_2 being collected than can be reacted in the SR, then excess CO_2 will have to be stored or vented. Similarly, if more H_2 is available than needed to react with the metabolic CO_2, then H_2 would need to be vented.

In the HyPA, the gases that are not absorbed are to be vented. That vent flow will contain some H_2 (not absorbed), some CH_4 (that was not reacted in the PPA), some residual H_2O, and other by-products of the PPA reactions. The RTM and related spreadsheet track the mass of those vented gases as the residuals that are not recovered in the H_2 absorption process.

The SR reaction of H_2 and CO_2 will use H_2 provided by the OGA and H_2 provided by the HyPA to react as much of the CO_2 as possible. The water generated by the SR flows to the WPA to be processed into potable water that can then be used to generate O_2 in the OGA.

IV. Test Case Results

The 60-day test case was simulated using the RTM model configured with information to define the RLS system modeled, the mission data for a nominal day of operations, and the component performance data. Crew operations are the same as documented in 2015, so inputs from metabolic processes and waste generation is the same, except that food is simulated as that actually consumed (as opposed to the required food, which includes rejected food and food that is lost in packaging).

With the OGA providing the O_2 needed to control cabin PPO_2, NASA identified the need to control the OGA rates to address fluctuations in cabin PPO_2 associated with nominal, then exercise, then sleep metabolic rates. Oscillations in cabin PPO_2 resulted without controls on the OGA rates using a constant rate combined with the small (relative to the ISS) volume of the exploration module. The RTM solution was to develop a control strategy that changed the OGA O_2 generation rate (via changing the inlet water flow rate) to keep the cabin PPO_2 within a narrow control band that did not require the PCS to supplement O_2 flow. That control and is illustrated in the cabin PPO_2 and other pressures shown in Figures 4 and 5.

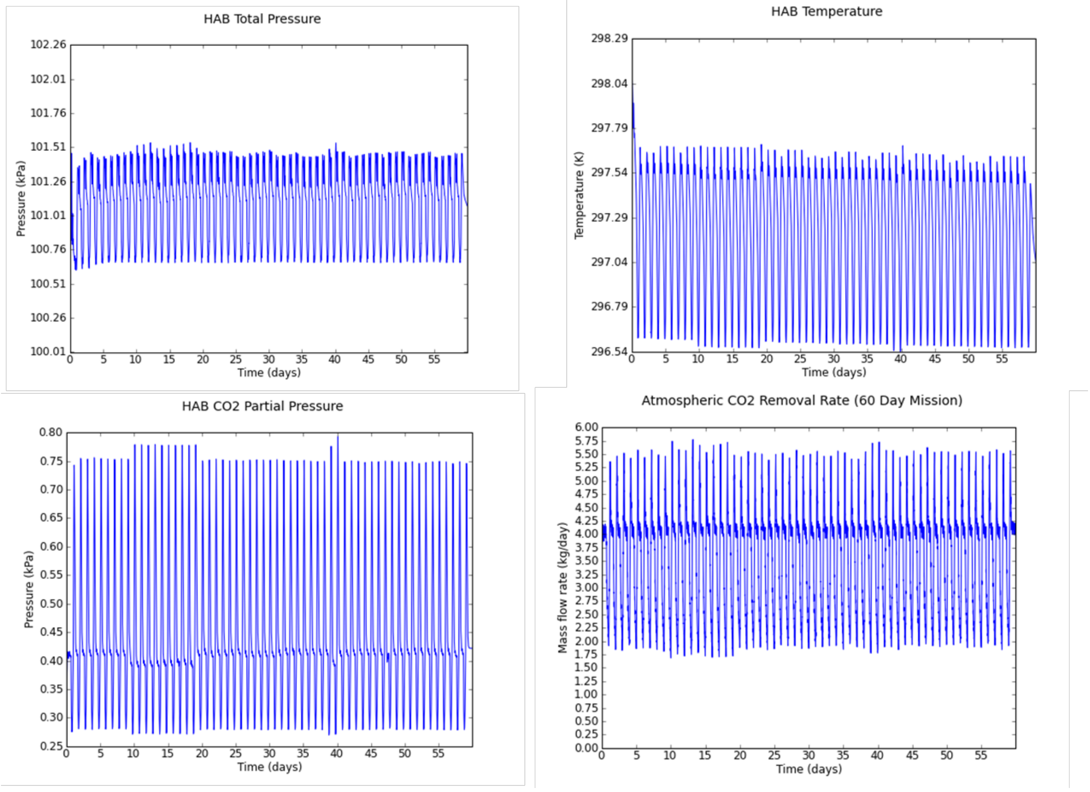


Figure 4. RTM 60-day mission. Habitation (HAB) module pressure, temperature, $PPCO_2$, and CO_2 removal rate.

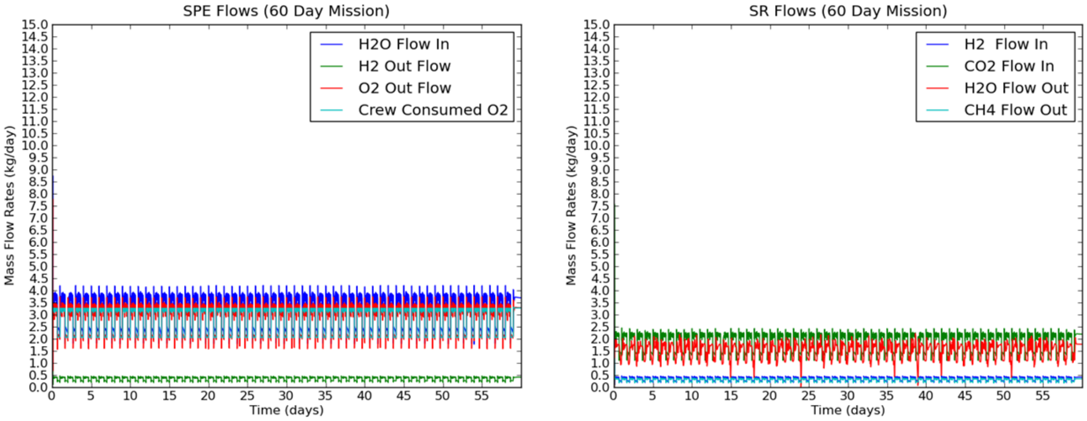


Figure 5. RTM 60-day mission. O_2 and CO_2 tank quantities, SR flows, and Solid Polymer Electrolyzer flows.

The changes of water routing that have distillate flowing to the WPA is reflected in the rates that water accumulates in tanks, as illustrated in Figure 6. Those profiles are very similar to those presented in the 2015 RTM paper.[1] Thus, the changes in water routing did not change the amount of water recovered by the RLS. The recovered water is shown in Figure 7.

The lower plots of Figure 7 show the quantity variations of the three potable water tanks. In the event all three tanks are full, the WPA water is flowed into an overflow tank so that the model can keep track of the excess water production. This trend can be observed in the last plot in Figure 7.

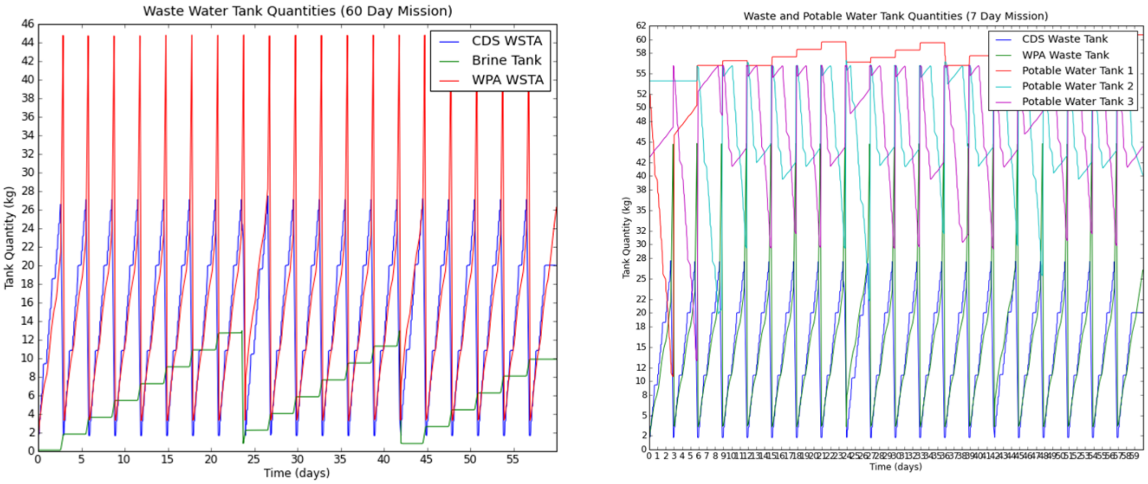


Figure 6. RTM 60-day mission. Waste and potable water tank quantities.

Figure 6 shows the CDS, Brine and WPA waste water and the related WPA and potable water tank quantities. The quantity of water produced during the 60 day EAM mission totals of more than 1000 kg of water that is reclaimed.

An excess of water (lower-right plot of Figure 7) is predicted of around 160 kg when those quantities are compared to the potable water used by the crew and by the Solid Polymer Electrolyzer (SPE) for electrolysis (lower-left plot). The excess is a result of the water content in food and the HMC trash processing that is not removed via the Potable Water Dispenser.

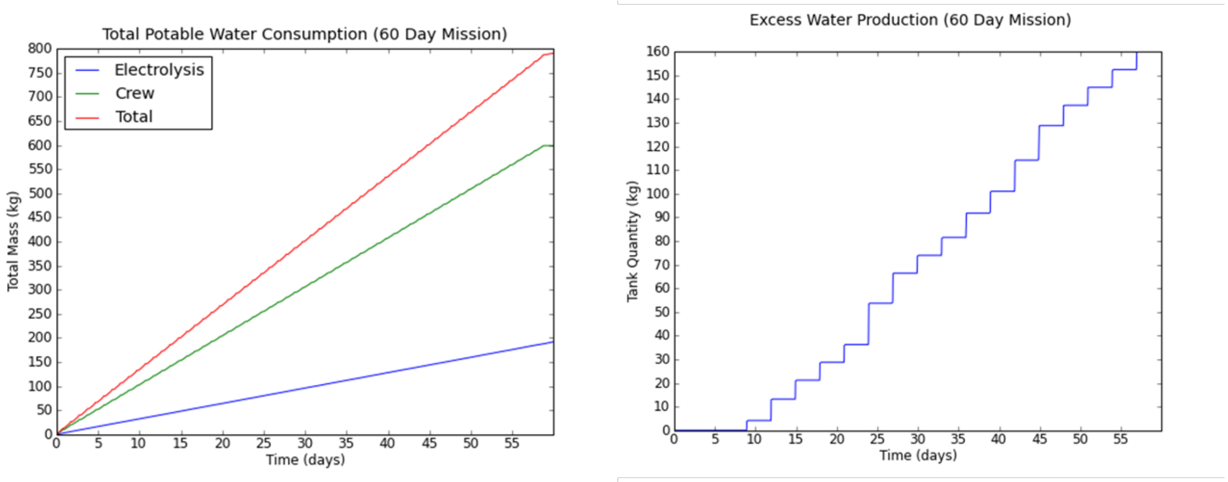


Figure 7. Waste and potable water production/consumption, and excess potable water production.

A. Mass Balance of Water and Oxygen during Operation of the Exploration Augmentation Module

Viewing the balance of H_2O for the vehicle requires considering all the potential H_2O processes because H_2O will shift from one process to another during the operation of the vehicle. Additionally, the crew use of H_2O has to consider several factors, including drinking H_2O, H_2O consumed via food, and H_2O recovered in trash products. Movement of H_2O around the vehicle will depend on operation of H_2O collection in the commode via urine, condensate in the CHX, and the HMC. Additionally, H_2O used in the OGA to create O_2 and H_2O 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 60 days of mission time just presented.

The RTM calculates where the inventory of H_2O is at any time and illustrates how the H_2O 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.

In a RLS, each of the subsystems balances inputs and outputs during the time it is operating. For example, Table 4 shows how 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 because the amount of H_2 available via the OGA and the PPA-HyPA is not enough to react all the CO_2 that is metabolically produced.

A vehicle mass balance must assess the inlets into the RLS and the outlets from the RLS.

Products entering the RLS are:

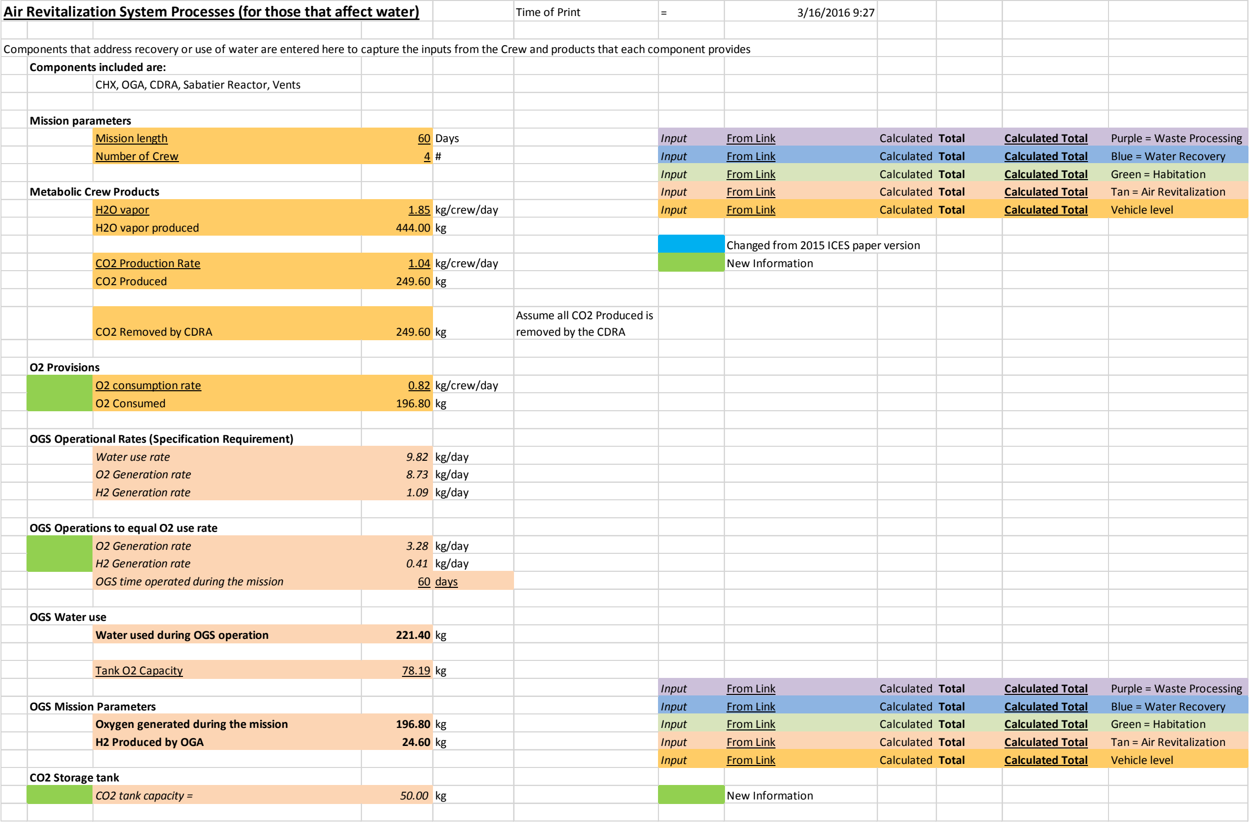
1) food,
2) trash (that is processed by the HMC), and
3) urine pretreat.

Products that exit the RLS are:

1) unused trash,
2) stored feces,
3) brine solids,
4) vented gases (unreacted CH_4 and unreacted H_2 and other PPA and HyPA products),
5) CO_2 (from CO_2 storage), and
6) atmosphere that is leaked from the cabin.
7) Water that is stored

The ARS inputs are shown in Table 3, whereas the new SR ARS processes are shown in Table 4. The new information for the PPA and HyPA plus the mission results are shown in Table 5. The color coding legend has been added to visually show the system the information relates to (via color) and the nature of the data being shown. This data shows the nature and the values used in calculations of the functions or the RLS equipment.

Table 3. ARS Inputs for the RTM



Air Revitalization System Processes (for those that affect water)					Time of Print	=	3/16/2016 9:27				
Components that address recovery or use of water are entered here to capture the inputs from the Crew and products that each component provides											
	Components included are:										
		CHX, OGA, CDRA, Sabatier Reactor, Vents									
	Mission parameters										
		Mission length	60	Days		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Purple = Waste Processing
		Number of Crew	4	#		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Blue = Water Recovery
						Input	From Link	Calculated	**Total**	**Calculated Total**	Green = Habitation
	Metabolic Crew Products					*Input*	From Link	Calculated	**Total**	**Calculated Total**	Tan = Air Revitalization
		H2O vapor	1.85	kg/crew/day		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Vehicle level
		H2O vapor produced	444.00	kg							
						🟦	Changed from 2015 ICES paper version				
		CO2 Production Rate	1.04	kg/crew/day		🟩	New Information				
		CO2 Produced	249.60	kg							
		CO2 Removed by CDRA	249.60	kg	Assume all CO2 Produced is removed by the CDRA						
	O2 Provisions										
	🟩	O2 consumption rate	0.82	kg/crew/day							
	🟩	O2 Consumed	196.80	kg							
	OGS Operational Rates (Specification Requirement)										
		Water use rate	*9.82*	kg/day							
		O2 Generation rate	*8.73*	kg/day							
		H2 Generation rate	*1.09*	kg/day							
	OGS Operations to equal O2 use rate										
	🟩	*O2 Generation rate*	*3.28*	kg/day							
	🟩	*H2 Generation rate*	*0.41*	kg/day							
		OGS time operated during the mission	60	days							
	OGS Water use										
		Water used during OGS operation	**221.40**	kg							
		Tank O2 Capacity	78.19	kg							
						Input	From Link	Calculated	**Total**	**Calculated Total**	Purple = Waste Processing
	OGS Mission Parameters					*Input*	From Link	Calculated	**Total**	**Calculated Total**	Blue = Water Recovery
		Oxygen generated during the mission	**196.80**	kg		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Green = Habitation
		H2 Produced by OGA	**24.60**	kg		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Tan = Air Revitalization
						Input	From Link	Calculated	**Total**	**Calculated Total**	Vehicle level
	CO2 Storage tank										
	🟩	*CO2 tank capacity =*	*50.00*	kg		🟩	New Information				

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 6. Data from the summary show that 365 kg of food is consumed, HMC-related trash produces 68 kg of distillate and 4kg of pretreat and 50 kg of stored CO_2 or 661 kg of RLS inputs. Out of the RLS, 175 kg of trash is sent to storage from the HMC, 58 kg of waste solids (fecal matter, solids in urine and BRIC solids), 137 kg of gases are either vented or leaked for a total stored or vented, and 280 kg of water is stored for processing for a total of 664 kg of outputs from the RLS. The small difference of 3 kg shows that mass is conserved.

Other pages of the mass balance spreadsheet address:

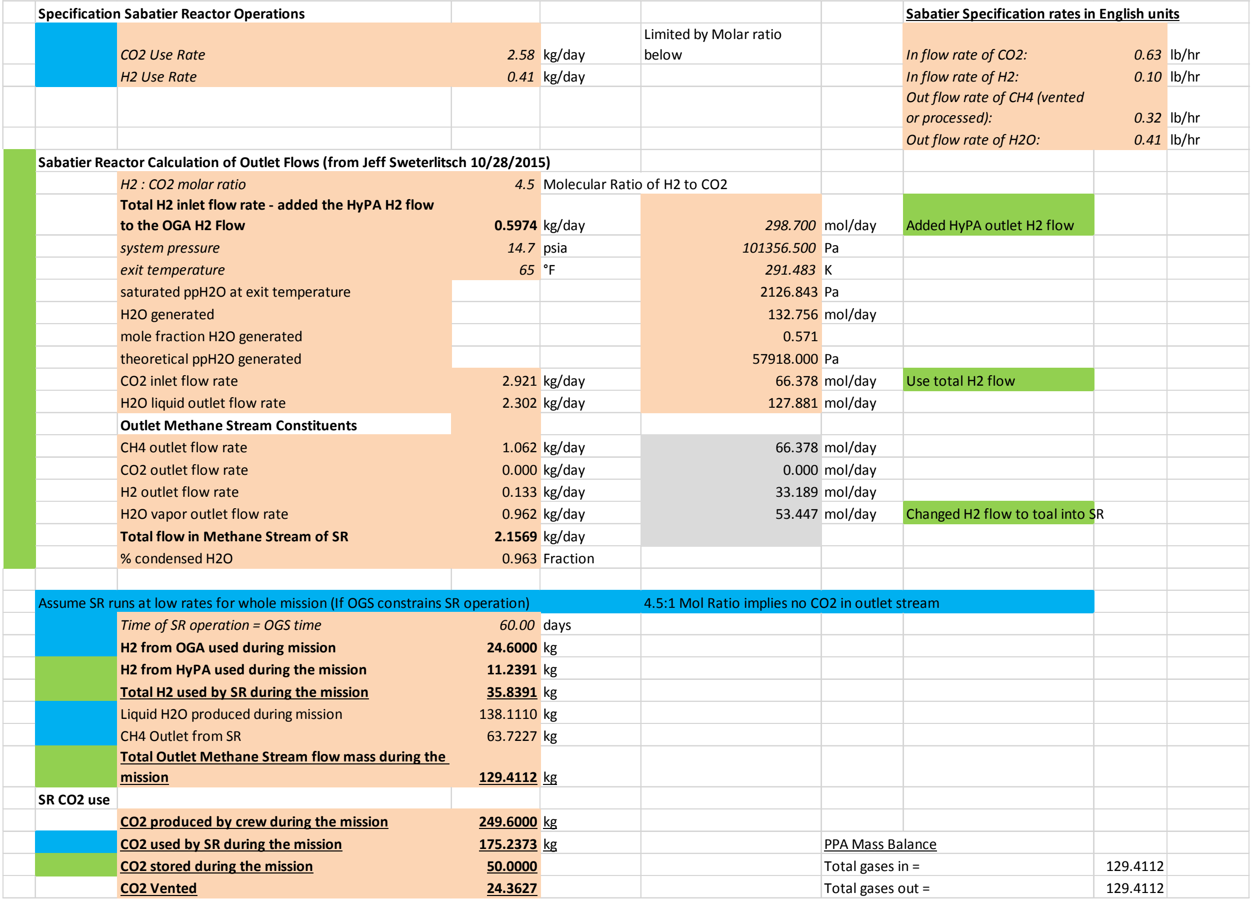
1) Mission parameters – to define the mission in length, the compliment of equipment used, reservoir sizes
2) Crew data – all the functions relating to crew consumption and production of resources
3) ARS processes – ARS functions related to water balance, PCS, CHX, SPE, SR operations
4) WRS processes – processes that provide potable water and those that recover H_2O
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 H_2O

The use of a RLS minimizes the loss of consumables, which must be addressed via provisions taken on exploration missions. Food, H_2O, O_2, N_2, 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 the Advanced Life Support Sizing Analysis Tool 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.

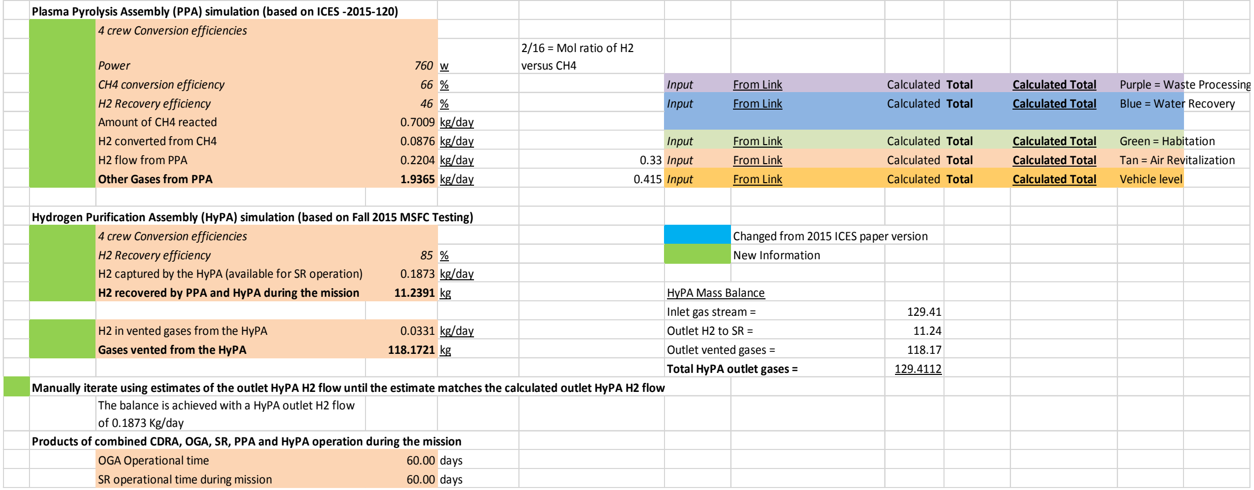
The mass balance of the integrated operation of the RLS components of the exploration habitat module is illustrated, and it shows that the flows of water in and out of components and the crew is balanced even though the logic of operations shifts the water resource from one part of the vehicle to another over the week of nominal operations

Table 4. Sabatier Data to Calculate Constituent Flows



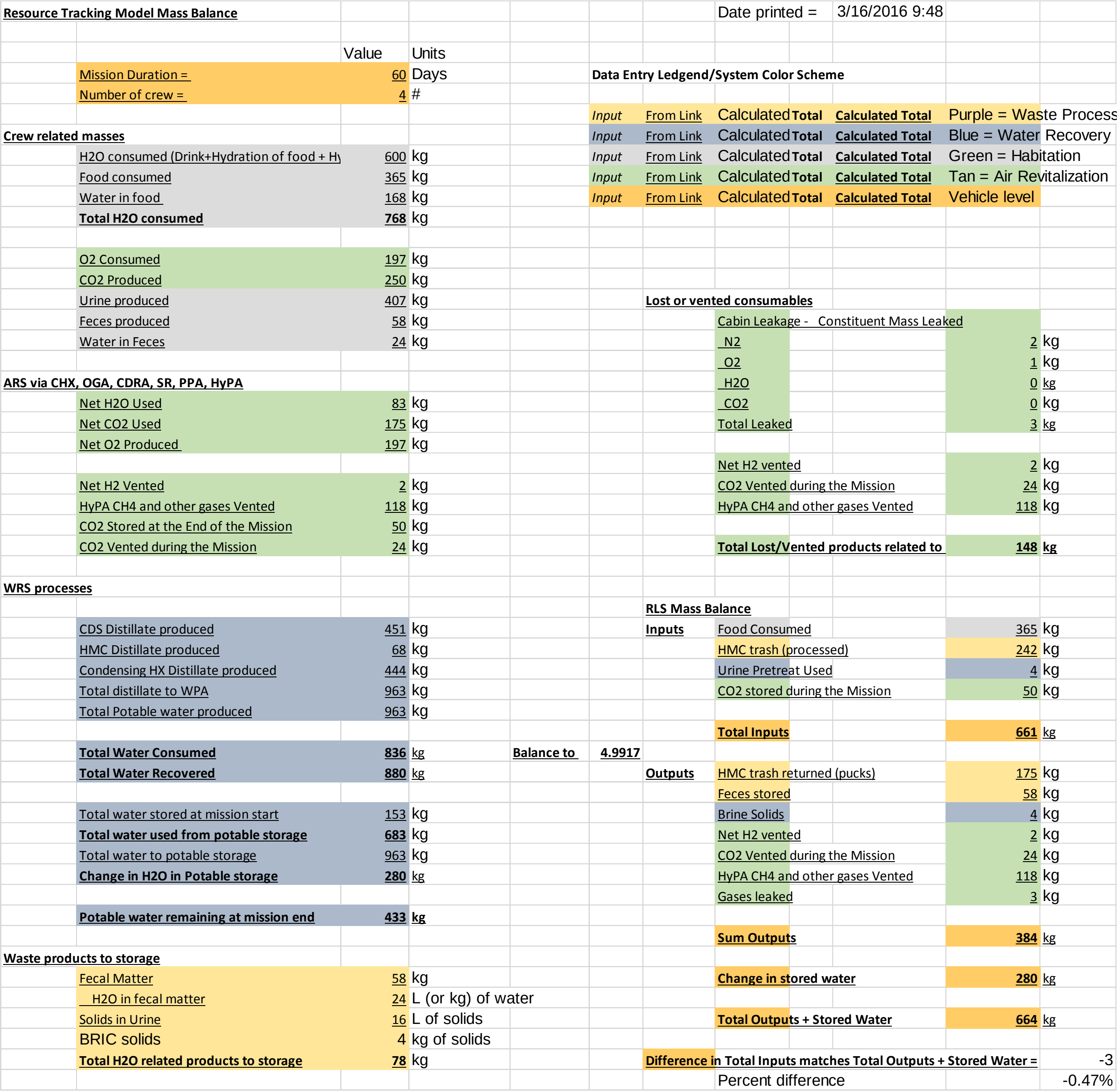
	Specification Sabatier Reactor Operations					**Sabatier Specification rates in English units**		
🟦	*CO2 Use Rate*	*2.58*	kg/day	Limited by Molar ratio below		*In flow rate of CO2:*	*0.63*	lb/hr
🟦	*H2 Use Rate*	*0.41*	kg/day			*In flow rate of H2:*	*0.10*	lb/hr
						Out flow rate of CH4 (vented or processed):	*0.32*	lb/hr
						Out flow rate of H2O:	*0.41*	lb/hr
🟩	**Sabatier Reactor Calculation of Outlet Flows (from Jeff Sweterlitsch 10/28/2015)**							
🟩	*H2 : CO2 molar ratio*	*4.5*	Molecular Ratio of H2 to CO2					
🟩	**Total H2 inlet flow rate - added the HyPA H2 flow to the OGA H2 Flow**	**0.5974**	kg/day	*298.700*	mol/day	Added HyPA outlet H2 flow		
🟩	*system pressure*	*14.7*	psia	*101356.500*	Pa			
🟩	*exit temperature*	*65*	°F	*291.483*	K			
🟩	saturated ppH2O at exit temperature			2126.843	Pa			
🟩	H2O generated			132.756	mol/day			
🟩	mole fraction H2O generated			0.571				
🟩	theoretical ppH2O generated			57918.000	Pa			
🟩	CO2 inlet flow rate	2.921	kg/day	66.378	mol/day	Use total H2 flow		
🟩	H2O liquid outlet flow rate	2.302	kg/day	127.881	mol/day			
🟩	**Outlet Methane Stream Constituents**							
🟩	CH4 outlet flow rate	1.062	kg/day	66.378	mol/day			
🟩	CO2 outlet flow rate	0.000	kg/day	0.000	mol/day			
🟩	H2 outlet flow rate	0.133	kg/day	33.189	mol/day			
🟩	H2O vapor outlet flow rate	0.962	kg/day	53.447	mol/day	Changed H2 flow to toal into SR		
🟩	**Total flow in Methane Stream of SR**	**2.1569**	kg/day					
🟩	% condensed H2O	0.963	Fraction					
	Assume SR runs at low rates for whole mission (If OGS constrains SR operation)			4.5:1 Mol Ratio implies no CO2 in outlet stream				
🟦	*Time of SR operation = OGS time*	*60.00*	days					
🟦	**H2 from OGA used during mission**	**24.6000**	kg					
🟩	**H2 from HyPA used during the mission**	**11.2391**	kg					
🟩	**Total H2 used by SR during the mission**	**35.8391**	kg					
🟦	Liquid H2O produced during mission	138.1110	kg					
🟦	CH4 Outlet from SR	63.7227	kg					
🟩	**Total Outlet Methane Stream flow mass during the mission**	**129.4112**	kg					
	SR CO2 use							
	CO2 produced by crew during the mission	**249.6000**	kg					
🟦	**CO2 used by SR during the mission**	**175.2373**	kg			PPA Mass Balance		
🟩	**CO2 stored during the mission**	**50.0000**				Total gases in =	129.4112	
	CO2 Vented	**24.3627**				Total gases out =	129.4112	

Table 5. PPA and HyPA Component Calculations and ARS Mission Masses



	Plasma Pyrolysis Assembly (PPA) simulation (based on ICES -2015-120)									
🟩	*4 crew Conversion efficiencies*									
🟩	*Power*	*760*	w	2/16 = Mol ratio of H2 versus CH4						
🟩	*CH4 conversion efficiency*	*66*	%		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Purple = Waste Processing
🟩	*H2 Recovery efficiency*	*46*	%		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Blue = Water Recovery
🟩	Amount of CH4 reacted	0.7009	kg/day							
🟩	H2 converted from CH4	0.0876	kg/day		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Green = Habitation
🟩	H2 flow from PPA	0.2204	kg/day	0.33	*Input*	From Link	Calculated	**Total**	**Calculated Total**	Tan = Air Revitalization
🟩	**Other Gases from PPA**	**1.9365**	kg/day	0.415	*Input*	From Link	Calculated	**Total**	**Calculated Total**	Vehicle level
	Hydrogen Purification Assembly (HyPA) simulation (based on Fall 2015 MSFC Testing)									
🟩	*4 crew Conversion efficiencies*				🟦	Changed from 2015 ICES paper version				
🟩	*H2 Recovery efficiency*	*85*	%		🟩	New Information				
🟩	H2 captured by the HyPA (available for SR operation)	0.1873	kg/day							
🟩	**H2 recovered by PPA and HyPA during the mission**	**11.2391**	kg		HyPA Mass Balance					
					Inlet gas stream =		129.41			
🟩	H2 in vented gases from the HyPA	0.0331	kg/day		Outlet H2 to SR =		11.24			
🟩	**Gases vented from the HyPA**	**118.1721**	kg		Outlet vented gases =		118.17			
					Total HyPA outlet gases =		129.4112			
🟩	**Manually iterate using estimates of the outlet HyPA H2 flow until the estimate matches the calculated outlet HyPA H2 flow**									
	The balance is achieved with a HyPA outlet H2 flow of 0.1873 Kg/day									
	Products of combined CDRA, OGA, SR, PPA and HyPA operation during the mission									
	OGA Operational time	60.00	days							
	SR operational time during mission	60.00	days							

Table 6. Mass Balance Spreadsheet Results for a 60-day Mission



Resource Tracking Model Mass Balance							Date printed =		3/16/2016 9:48		
		Value	Units								
	Mission Duration =	60	Days		**Data Entry Ledgend/System Color Scheme**						
	Number of crew =	4	#								
					Input	From Link	Calculated	**Total**	**Calculated Total**	Purple = Waste Process	
Crew related masses					*Input*	From Link	Calculated	**Total**	**Calculated Total**	Blue = Water Recovery	
	H2O consumed (Drink+Hydration of food + Hy	600	kg		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Green = Habitation	
	Food consumed	365	kg		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Tan = Air Revitalization	
	Water in food	168	kg		*Input*	From Link	Calculated	**Total**	**Calculated Total**	Vehicle level	
	Total H2O consumed	**768**	kg								
	O2 Consumed	197	kg								
	CO2 Produced	250	kg								
	Urine produced	407	kg			**Lost or vented consumables**					
	Feces produced	58	kg				Cabin Leakage - Constituent Mass Leaked				
	Water in Feces	24	kg				N2			2	kg
							O2			1	kg
ARS via CHX, OGA, CDRA, SR, PPA, HyPA							H2O			0	kg
	Net H2O Used	83	kg				CO2			0	kg
	Net CO2 Used	175	kg				Total Leaked			3	kg
	Net O2 Produced	197	kg								
							Net H2 vented			2	kg
	Net H2 Vented	2	kg				CO2 Vented during the Mission			24	kg
	HyPA CH4 and other gases Vented	118	kg				HyPA CH4 and other gases Vented			118	kg
	CO2 Stored at the End of the Mission	50	kg								
	CO2 Vented during the Mission	24	kg				**Total Lost/Vented products related to**			**148**	**kg**
WRS processes											
						RLS Mass Balance					
	CDS Distillate produced	451	kg			**Inputs**	Food Consumed			365	kg
	HMC Distillate produced	68	kg				HMC trash (processed)			242	kg
	Condensing HX Distillate produced	444	kg				Urine Pretreat Used			4	kg
	Total distillate to WPA	963	kg				CO2 stored during the Mission			50	kg
	Total Potable water produced	963	kg								
							Total Inputs			**661**	kg
	Total Water Consumed	**836**	kg	**Balance to**	**4.9917**						
	Total Water Recovered	**880**	kg			**Outputs**	HMC trash returned (pucks)			175	kg
							Feces stored			58	kg
	Total water stored at mission start	153	kg				Brine Solids			4	kg
	Total water used from potable storage	**683**	kg				Net H2 vented			2	kg
	Total water to potable storage	963	kg				CO2 Vented during the Mission			24	kg
	Change in H2O in Potable storage	**280**	kg				HyPA CH4 and other gases Vented			118	kg
							Gases leaked			3	kg
	Potable water remaining at mission end	**433**	**kg**								
							Sum Outputs			**384**	kg
Waste products to storage											
	Fecal Matter	58	kg				**Change in stored water**			**280**	kg
	H2O in fecal matter	24	L (or kg) of water								
	Solids in Urine	16	L of solids				**Total Outputs + Stored Water**			**664**	kg
	BRIC solids	4	kg of solids								
	Total H2O related products to storage	**78**	kg			**Difference in Total Inputs matches Total Outputs + Stored Water =**					-3
							Percent difference				-0.47%

V. Trade Studies

The RTM has been used for several trade studies as an example of the types of assessments that the RTM can support. The RTM can show how the transient behavior of the integrated RLS changes with performance changes in the variety of components. It can also show how the trends change when alternate technology is used for a particular function.

The RTM spreadsheet can be used to quickly address the overall mission resource use for changes in a technology performance or architecture. The spreadsheet can address how the overall mission resources are used, but it cannot establish the trends in resource use across the RLS.

A. Study of the Changes Associated with the Addition of the Post Sabatier Reactor Processing of the Integrated Methane Stream

The initial trade study focused on the benefits of the addition of the PPA and HyPA assemblies for reusing H_2 to recover more of the O_2 from metabolic CO_2. The recovery of the O_2 increases the amount of CO_2 reacted, thus reducing the amount of CO_2, CH_4, and other SR waste gases that have to be vented. It also increases the amount of water generated in the SR, thus reducing the net amount of water required for the SR and OGA operations. The data in Table 7 shows that the changes are significant over the 60 days of mission time assessed. The benefits would continue for the length of an exploration mission. The trade of the development cost versus the benefits in achieving better closure would need to consider an actual mission and the cost of resources.

This trade shows that while the O_2 produced and the H_2 provided by the OGA is the same, the amount of CO_2 used increases by 55 kg and the net water used drops from 127 kg to 83 kg. The net gases vented increases by 9 kg (related to increased CO_2 use).

The overall gain achieved by recovering H2 from the CH4 waste stream of the SR is 33 kg for the 60 day mission. That is a significant gain and the gain would be greater if the mission to be flown is longer.

VI. Overview and Conclusions

The refinement of the RTM involved changes to reflect plans for routing fluids and the inclusion of new ARS components to more completely recover the O_2 from metabolic CO_2.

The refined version of the RTM was used to predict the balance of the variety of RLS fluids and gases for a simulated 60-day period of nominal exploration vehicle operations. The inclusion of a PPA and related HyPA provides added closure of the RLS. However, even including those components, recovering the H_2 from SR wastes, and reusing the H_2, there is still not enough H_2 to completely recover the O_2 from crew-generated CO_2. Recovering and reusing the H_2 in the SR outlet stream improves closure by using 55 kg more of the CO_2 and reducing the net water used in the ARS from 79 kg to 24 kg.

Table 7. The Mission-Level Effects of Recovering H_2 from the SR CH_4 Stream

Using a PPA and HyPA to recycle H2				
Sabatier Reactor Calculation of Outlet Flows (from Jeff Sweterlitsch 10/28/2015)				
H2 : CO2 molar ratio	*4.5*	Molecular Ratio of H2 to CO2		
Total H2 inlet flow rate - added the HyPA H2 flow to the OGA H2 Flow	**0.5974**	kg/day	*298.700*	mol/day
system pressure	*14.7*	psia	*101356.500*	Pa
exit temperature	*65*	°F	*291.483*	K
saturated ppH2O at exit temperature			2126.843	Pa
H2O generated			132.756	mol/day
mole fraction H2O generated			0.571	
theoretical ppH2O generated			57918.000	Pa
CO2 inlet flow rate	2.921	kg/day	66.378	mol/day
H2O liquid outlet flow rate	2.302	kg/day	127.881	mol/day
Outlet Methane Stream Constituents				
CH4 outlet flow rate	1.062	kg/day	66.378	mol/day
CO2 outlet flow rate	0.000	kg/day	0.000	mol/day
H2 outlet flow rate	0.133	kg/day	33.189	mol/day
H2O vapor outlet flow rate	0.962	kg/day	53.447	mol/day
Total flow in Methane Stream of SR	**2.1569**	kg/day		
% condensed H2O	0.963	Fraction		
			4.5:1 Mol Ratio implies no CO2 in outlet stream	
Assume SR runs at low rates for whole mission (If OGS constrains SR operation)				
Time of SR operation = OGS time	*60.00*	days		
H2 from OGA used during mission	**24.6000**	kg		
H2 from HyPA used during the mission	**11.2391**	kg		
Total H2 used by SR during the mission	**35.8391**	kg		
Liquid H2O produced during mission	138.1110	kg		
CH4 Outlet from SR	63.7227	kg		
Total Outlet Methane Stream flow mass during the mission	**129.4112**	kg		
SR CO2 use				
CO2 produced by crew during the mission	**249.6000**	kg		
CO2 used by SR during the mission	**175.2373**	kg		
CO2 stored during the mission	**50.0000**			
CO2 Vented	**24.3627**			
Plasma Pyrolysis Assembly (PPA) simulation (based on ICES -2015-120)				
4 crew Conversion efficiencies				
Power	*760*	w		
CH4 conversion efficiency	*66*	%		
H2 Recovery efficiency	*46*	%		
Amount of CH4 reacted	0.7009	kg/day		
H2 converted from CH4	0.0876	kg/day		
H2 flow from PPA	0.2204	kg/day		
Other Gases from PPA	**1.9365**	kg/day		
Hydrogen Purification Assembly (HyPA) simulation (based on Fall 2015 MSFC Testing)				
4 crew Conversion efficiencies				
H2 Recovery efficiency	*85*	%		
H2 captured by the HyPA (available for SR op	0.1873	kg/day		
H2 recovered by PPA and HyPA during the r	**11.2391**	kg		
H2 in vented gases from the HyPA	0.0331	kg/day		
Gases vented from the HyPA	**118.1721**	kg		
Products of combined CDRA, OGA, SR, PPA and HyPA operation during the mission				
OGA Operational time	60.00	days		
SR operational time during mission	60.00	days		
Water Used by OGA	**221.40**	kg		
O2 Produced by OGA	**196.80**	kg		
H2 Produced by OGA	**24.60**	kg		
H2 Recovered by the PPA-HyPA	**11.24**	kg		
SR H2 used	**35.84**	kg		
SR CO2 used	**175.24**	kg		
SR H2O produced	**138.11**	kg		
Net O2 Produced	**196.80**	**kg**		
Net H2O Used	**83.29**	**kg**		
Net CO2 Used	**175.24**	**kg**		
Net H2 vented	**1.98**	**kg**		
Net HyPA gases Vented	**118.17**	**kg**		
Net CO2 Vented during the Mission	**24.36**	**kg**		
CO2 Stored at end of mission	**50.00**	**kg**		

ARS resources when venting the Sabatier waste Gas Stream			
Sabatier Reactor Calculation of Outlet Flows (from Jeff Sweterlitsch 10/28/2015)			
H2 : CO2 molar ratio	*4.5*	Molecular Ratio of H2 to (	
Total H2 inlet flow rate	**0.4100**	kg/day	*205.000*
system pressure	*14.7*	psia	*101356.500*
exit temperature	*65*	°F	*291.483*
saturated ppH2O at exit temperature			2126.843
H2O generated			91.111
mole fraction H2O generated			0.571
theoretical ppH2O generated			57918.000
CO2 inlet flow rate	2.004	kg/day	45.556
H2O liquid outlet flow rate	1.580	kg/day	87.765
Outlet Methane Stream Constituents			
CH4 outlet flow rate	0.729	kg/day	45.556
CO2 outlet flow rate	0.000	kg/day	0.000
H2 outlet flow rate	0.091	kg/day	22.778
H2O vapor outlet flow rate	0.968	kg/day	53.756
Total flow in Methane Stream of SR	**1.7876**	kg/day	
% condensed H2O	0.963	Fraction	
Assume SR runs at low rates for whole mission (If OGS constrains SR operation)			
Time of SR operation = OGS time	*60.00*	days	
H2 from OGA used during mission	**24.6000**	kg	
H2 from HyPA used during the mission	**0.0000**	kg	
Total H2 used by SR during the mission	**24.6000**	kg	
Liquid H2O produced during mission	94.7866	kg	
CH4 Outlet from SR	43.7333	kg	
Total Outlet Methane Stream flow mass during the mission	**107.2560**	kg	
SR CO2 use			
CO2 produced by crew during the mission	**249.6000**	kg	
CO2 used by SR during the mission	**120.2667**	kg	
CO2 stored during the mission	**50.0000**		
CO2 Vented	**79.3333**		
Plasma Pyrolysis Assembly (PPA) simulation (based on ICES -2015-120)			
4 crew Conversion efficiencies			
Power	*760*	w	
CH4 conversion efficiency	*66*	%	
H2 Recovery efficiency	*46*	%	
Amount of CH4 reacted	NA	kg/day	
H2 converted from CH4	NA	kg/day	
H2 flow from PPA	NA	kg/day	
Other Gases from PPA	NA	kg/day	
Hydrogen Purification Assembly (HyPA) simulation (based on Fall 2015 MSFC Testing)			
4 crew Conversion efficiencies			
H2 Recovery efficiency	*85*	%	
H2 captured by the HyPA (available for SR operation)	NA	kg/day	
H2 recovered by PPA and HyPA during the mission	NA	kg	
H2 in vented gases from the HyPA	NA	kg/day	
Gases vented from the HyPA	NA	kg	
Products of combined CDRA, OGA, SR, PPA and HyPA operation during the mission			
OGA Operational time	60.00	days	
SR operational time during mission	60.00	days	
Water Used by OGA	**221.40**	kg	
O2 Produced by OGA	**196.80**	kg	
H2 Produced by OGA	**24.60**	kg	
H2 Recovered by the PPA-HyPA	**0.00**	kg	
SR H2 used	**24.60**	kg	
SR CO2 used	**120.27**	kg	
SR H2O produced	**94.79**	kg	
Net O2 Produced	**196.80**	**kg**	
Net H2O Used	**126.61**	**kg**	
Net CO2 Used	**120.27**	**kg**	
Net H2 vented	**0.09**	**kg**	
Net SR gases Vented	**107.26**	**kg**	
Net CO2 Vented during the Mission	**79.33**	**kg**	
CO2 Stored at end of mission	**50.00**	**kg**	

VII. 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 simulate mission scenarios using exploration vehicles employing RLS technologies to conserve limited resources.

The RTM will be used for the variety of simulation needs that technology developers and mission planners develop for exploration missions.

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