Next Generation Life Support Project Status

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Next Generation Life Support (NGLS) is one of more than 20 technology development projects sponsored by NASA's Game Changing Development Program. The NGLS Project develops selected life support technologies needed for humans to live and work productively in space, with focus on technologies for future use in spacecraft cabin and space suit applications. Over the last 3 years, NGLS had five main project elements: Variable Oxygen Regulator (VOR), Rapid Cycle Amine (RCA) swing bed, High Performance Extravehicular Activity (EVA) Glove (HPEG), Alternative Water Processor (AWP) and Series-Bosch Carbon Dioxide Reduction. The RCA swing bed, VOR and HPEG tasks are directed at key technology needs for the Portable Life Support System (PLSS) and pressure garment for an Advanced Extravehicular Mobility Unit (EMU). Focus is on prototyping and integrated testing in cooperation with the Advanced Exploration Systems (AES) Advanced EVA Project. The HPEG Element, new this fiscal year, includes the generation of requirements and standards to guide development and evaluation of new glove designs. The AWP and Bosch efforts focus on regenerative technologies to further close spacecraft cabin atmosphere revitalization and water recovery loops and to meet technology maturation milestones defined in NASA's Space Technology Roadmaps. These activities are aimed at increasing affordability, reliability, and vehicle self-sufficiency while decreasing mass and mission cost, supporting a capability-driven architecture for extending human presence beyond low-Earth orbit, along a human path toward Mars. This paper provides a status of current technology development activities with a brief overview of future plans.

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Nomenclature

Cl^- = chloride
CO_2 = carbon dioxide
d = day
ft^2 = square foot
HCO_3^- = bicarbonate
K^+ = potassium
kg = kilograms
lb = pounds
$LiOH$ = lithium hydroxide
$MetOx$ = metal oxide
mg = milligrams
mg/L = milligrams per liter
N_2 = nitrogen
Na^+ = sodium
NH_4^+ = ammonium
NO_x^- = nitrates and nitrites
O_2 = oxygen
PO_4^{-3} = phosphate
$psid$ = pounds per square inch absolute
$psid$ = pounds per square inch differential
sec = seconds
SO_4^{-2} = sulfate
Zn = Zinc

I. Introduction

The Next Generation Life Support Project (NGLS) is one of approximately 23 active technology development projects managed by the Game Changing Development Program (GCDP) within NASA's Space Technology Mission Directorate (STMD). Addressing technology areas found in the agency's Technology Roadmaps as prioritized by the National Academies,[1] STMD's Programs and Projects deliver innovative and transformative solutions to dramatically improve technological capabilities through multiphased technology development efforts, demonstrations, competitive opportunities, and partnerships, engaging government, industry, and academia. Guidance for investments is given in the NASA Strategic Space Technology Investment Plan.[2] GCDP seeks to identify and rapidly mature innovative/high impact capabilities and technologies that may lead to entirely new approaches for the Agency's future space missions and invests in mid-Technology Readiness Level (TRL) technologies using focused 2- to 3-year development efforts. NGLS was initiated under GCDP at the beginning of Fiscal Year (FY) 2012 and directed to develop life support technologies (including atmospheric revitalization, water recovery, and space suit technologies) needed for humans to live and work productively in space.[3] This paper will provide a brief overview of the NGLS project, its goals and performance parameters and a status of each technology development element, and close with a brief discussion of future plans.

II. Project Overview

The current NGLS portfolio includes five technology development elements: Variable Oxygen Regulator (VOR), Rapid Cycle Amine (RCA) swing bed, Alternative Water Processor (AWP), High Performance Extravehicular Activity (EVA) Glove (HPEG) and Series-Bosch Carbon Dioxide Reduction. A project "element" is a task or activity leading to the development of a specific, unique technology.

Project organization follows NASA's Research and Technology Program and Project Management Requirements, NPR 7120.8.[4] The work breakdown structure (WBS) for NGLS is shown in Figure 1. When NGLS was initiated in FY2012, a field center designator was used for the last two digits of each WBS. Beginning in FY2014 NGLS was directed to include a center designator in the second 2-digit position of the WBS for all new project elements that were added. Technical work is performed across four NASA field centers - Johnson Space Center, Ames Research Center, Marshall Space Flight Center and Kennedy Space Center - with involvement of several outside institutions including Texas Tech University, University of Puerto Rico,

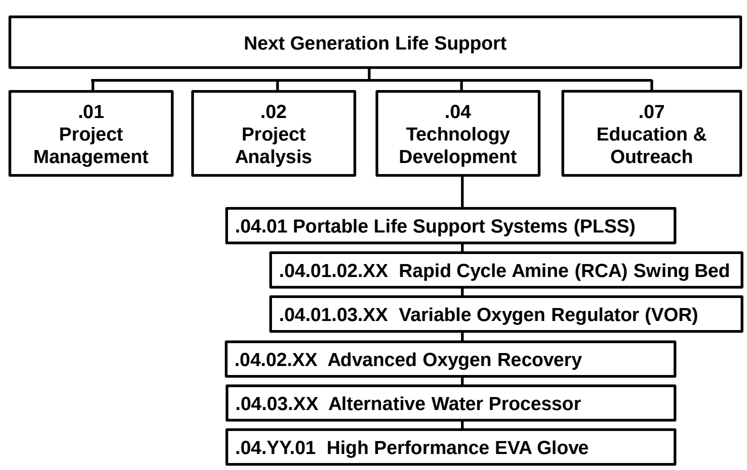

Figure 1. Work Breakdown Structure (WBS) for NGLS. *XX and YY are placeholders for 2-digit center designators.*

Iowa State University, Carleton Technologies, United Technologies – Aerospace Systems, Porifera, zNano and Aquaporin (Figure 2).

III. Project Schedule Overview

A top-level schedule for the NGLS Project is depicted in Figure 3. The first three elements - VOR, RCA and AWP - were initiated at the beginning of FY2012 and will end in FY2014, after three years of investment. Series-Bosch has been funded as a low level civil service labor only task since FY2013 under the Advanced Oxygen Recovery (AOR) Element. AOR will transition to a competitively funded activity in FY15. HPEG was initiated in FY2014 and will continue through FY2016. Additional discussion will be given in Section V under the status of each project element.

IV. Overview of Project Goals and Performance Parameters

The primary project goal is to advance TRL and infuse technologies into Advanced Exploration Systems (AES) system demonstrations. Technologies were chosen that would provide new capabilities not found in existing NASA systems. Most selected technologies address major challenges identified by NASA's Space Technology Roadmap for Human Health, Life Support and Habitation Systems.[1] The RCA Element addresses the challenge "In–situ regenerable technologies that will allow on-back regeneration and enable sustained EVA". The VOR Element addresses the challenge "Capability to treat decompression sickness in the suit, allow for rapid vehicle egress, and provide flexibility for interfacing the suit with multiple vehicles that may operate at different pressures". The AWP Element addresses the challenge "Recover water from additional sources, including hygiene and laundry" and seeks to make progress toward the 2020-2024 milestone that calls for water recovery augmented by biological systems. The AOR Element addresses the challenge "Increase recovery of O_2 from CO_2" and seeks to make progress toward the 2011-2014 and 2015-2019 milestones to achieve 75%, then 100% oxygen recovery, respectively.

Key performance parameters (KPPs) for four principal NGLS technologies are given in Table 1. Success is reached when at least the minimum threshold value is achieved, although ultimately it is desirable to achieve the research and technology development goal. NGLS successfully met most KPPs. Water and carbon dioxide (CO_2) removal rates for the RCA will be calculated later this fiscal year when the Portable Life Support System (PLSS) 2.0 integrated testing is completed in cooperation with the AES EVA Systems Project. Prototypes of HPEG will not be available for 1 to 2 years. All technologies must ultimately be compatible with cabin pressure and oxygen levels of future spacecraft.[30] Additional discussion will be given in Section V under the status of each project element.

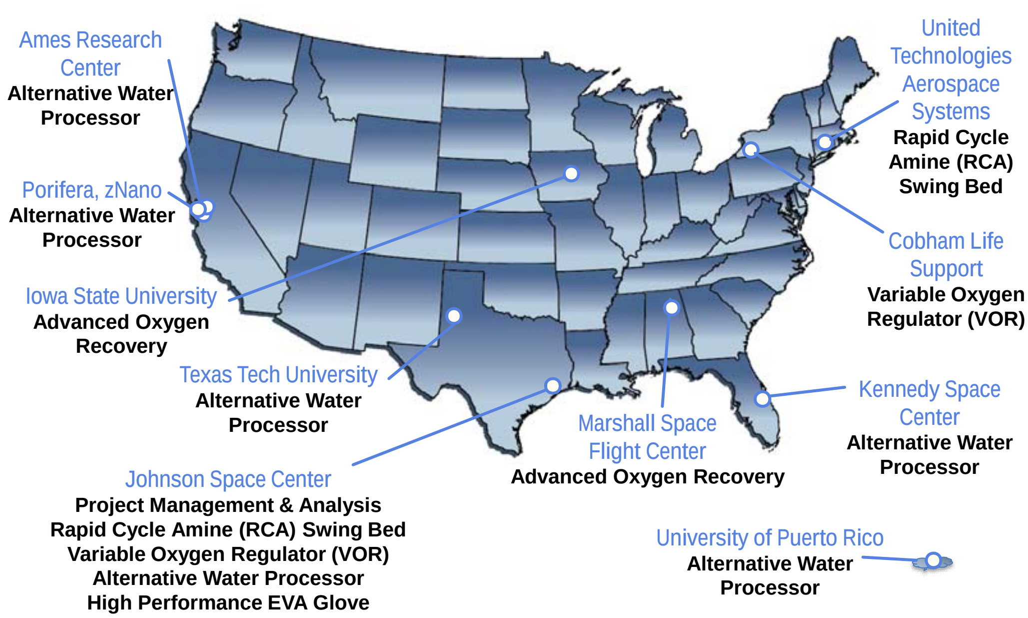

Figure 2. Geographical participation in the NGLS Project.

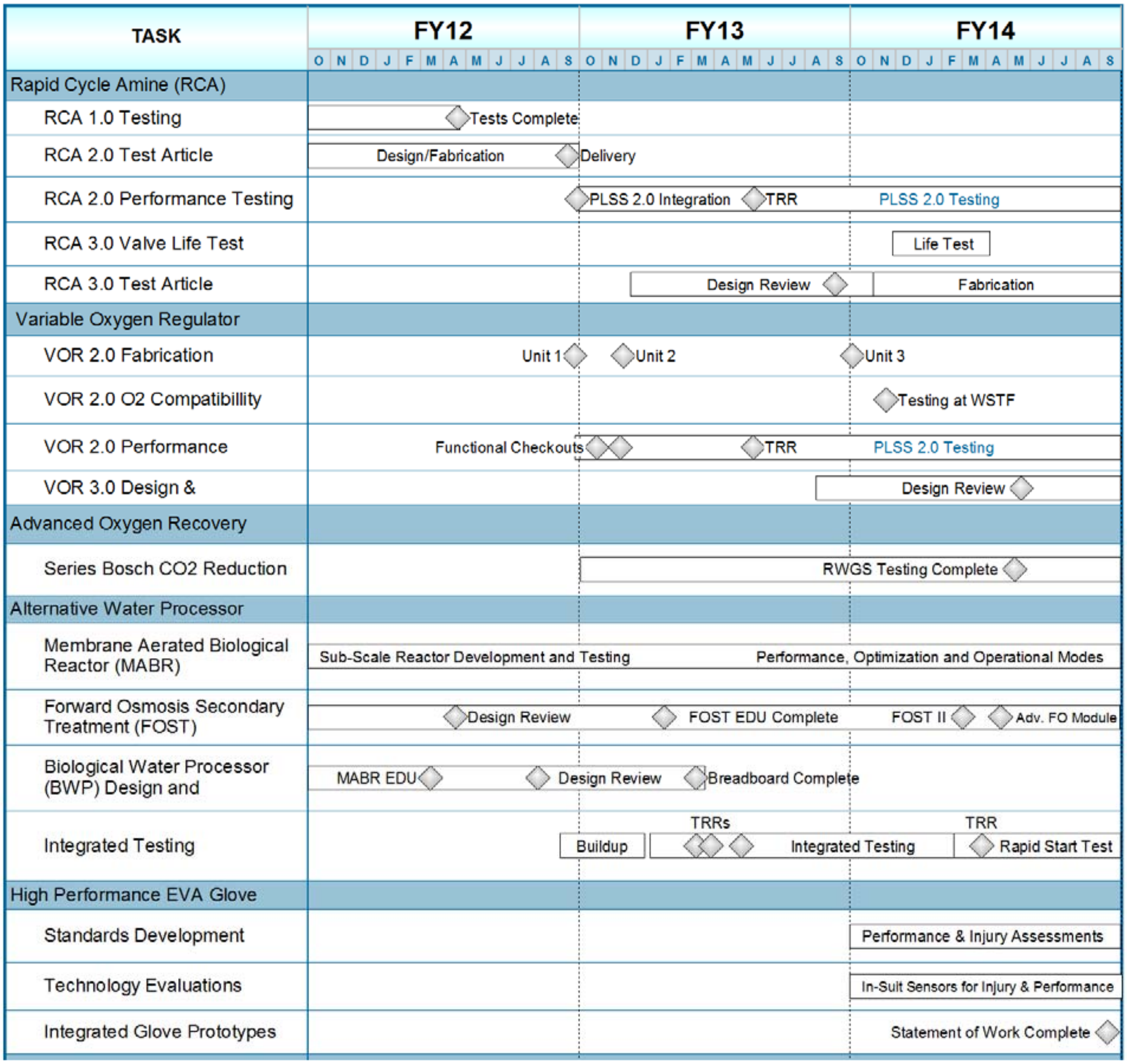

Figure 3. Top-level schedule for the NGLS Project for FY2012 through FY2014.

V. Project Element Status

The following sections provide a discussion of each Project Element, including a top level description of the technology, development objectives and status. A summary of findings from testing will be given when available, as well as citations for more detailed information and test results.

A. Rapid Cycle Amine Swingbed (RCA)

The focus of the RCA Element is to develop an integrated CO_2 removal and humidity control system that can be regenerated in real time during an EVA. Not only does this capability eliminate consumables associated with non-regenerable technologies, the RCA eliminates off-suit regeneration that requires ancillary equipment and power, and eliminates CO_2 scrubbing as an EVA duration limitation.[5,6,7] The amine used in the swing bed also removes water vapor from the suit ventilation loop, thereby eliminating the need for a condensing heat exchanger, slurper, and rotary separator, as is used with the current Advanced Extravehicular Mobility Unit (EMU). The project's target of a mass reduction of 67% as compared to the state-of-the-art (SOA) was exceeded (Table 1). Additional detail on the design and early development of the technology can be found elsewhere.[8,9]

Table 1. Key Performance Parameters.

Description	State of the Art (SOA)	Threshold Values	R&TD Goals	Measured Value
Rapid Cycle Amine (RCA) Swing Bed				
CO_2 removal system mass (kg)	60.8[a]	15.5	5	8.3
System Life (EVA uses)	25	50	100+	>100[b]
H_2O removal rate (g/min)	1.49	1.49	>1.49	TBD[c]
CO_2 removal rate (g/min)	2.26	2.26	3.04	TBD[c]
Variable Oxygen Regulator (VOR)				
Pressure Settings	2	5	84**	7,400
Pressure Range (psi)	~0.9 & 4.3	0.3-8.4	0-8.4	0 - 8.4
Contamination Tolerance	< 2mg/ft^2	>2 mg/ft^2	50 mg/ ft^2	100 mg/ ft^2
Mass (lb)	8	6	3.5	3.96
Alternative Water Processor (AWP)				
Wastewater Recycling (Full Wastewater)[d]	0%[e]	85%	>95%	92%
Consumable Reduction from SOA	-	20%	50%	29%
High Performance EVA Glove (HPEG)				
Mobility (% of Barehanded Capability)	20%	40%	60%	TBD[f]
Durability (Useful Life)	7 EVAs	14 EVAs	50 EVAs	TBD[f]
Injury Potential (% of Total Reported Incidents)	47%	35%	30%	TBD[f]
Advanced Oxygen Recovery (AOR)				
Recovery of O_2 from CO_2 (%)	<50%	75%	>95%	TBD[f]

[a]MetOx plus regenerator unit
[b]Based on life testing of RCA ball valve test article. Valve survived >105,000 cycles, equivalent to ~2,100 EVAs.
[c]To be determined following completion of PLSS 2.0 Integrated Testing late in fiscal year 2014.
[d]Exploration wastewater including urine, condensate, hygiene, shave, oral and laundry. [e]SOA only processes urine and condensate.
[f]To be determined in subsequent years after prototypes are developed and tested.

Significant accomplishments since the beginning of the project include (see also schedule in Figure 3):

- Completion of testing of first generation hardware (RCA 1.0). Data were used to inform the design of second generation hardware and develop algorithms for its control system.
- Design and fabrication of second generation hardware (RCA 2.0).[10]
- Integration of the RCA 2.0 test article into the PLSS 2.0 test article and initiation of performance testing as part of the integrated test (Figure 4A). At the completion of this testing the RCA is expected to be at a TRL of 5.
- Design and fabrication of the Suited Manikin Test Apparatus (SMTA) and Ventilation Test Stand (Figure 4B).
- Design of third generation (RCA 3.0) hardware (Figure 4C).[11] Differences between RCA 1.0, 2.0 and 3.0 are given in Table 2.
- Fabrication and life testing of the RCA 3.0 valve assembly. Fabrication of the full RCA 3.0 test article is expected to be completed by the end of FY2014. This unit will be rated for use with 100% oxygen. Once environments testing has been completed (NGLS) and following future human testing (to be conducted by the AES EVA Systems Project) RCA 3.0 will be at a TRL of 6.

The SMTA and Ventilation Test Stand were developed to perform unit functional testing of RCA hardware with a simulated relevant environment.[12] The SMTA makes use of a Space Suit Assembly Simulator (SSAS) to provide an accurate atmospheric volume. A manikin inside the SSAS simulates a crew member's displacement of atmospheric volume, and duplicates ventilation flow patterns in a similar way that a crewmember would in a donned suit. In addition, the manikin is configured to simulate human breathing patterns. Environmental conditions within the SMTA are controlled and include pressure, humidity, CO_2 partial pressure and temperature. The manikin wears a Liquid Cooling and Ventilation Garment. A range of human metabolic loads can be simulated. For cost and safety,

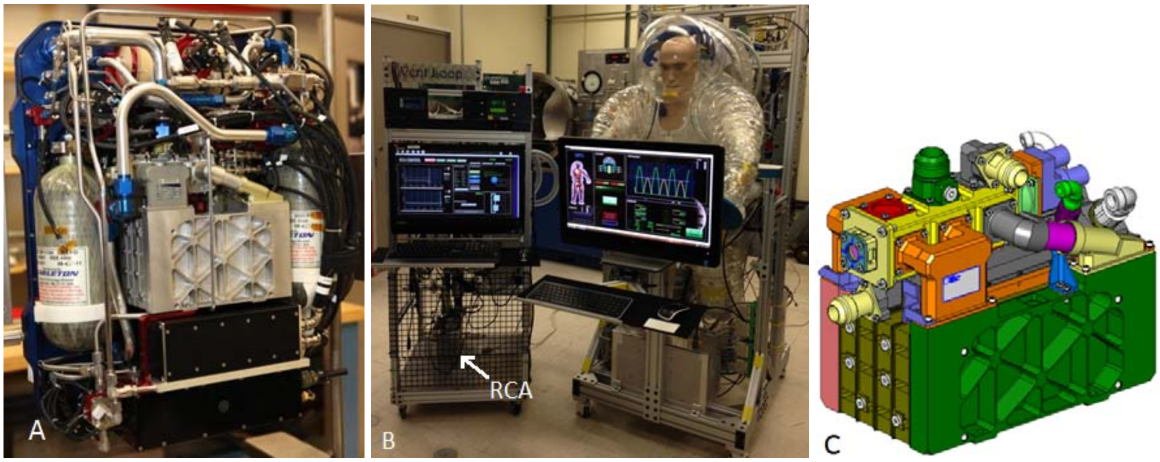

Figure 4. A: Rapid Cycle Amine (RCA) 2.0 (center of photo) and Variable Oxygen Regulators (atop each pressure bottle) integrated into the Portable Life Support System (PLSS) 2.0 test article. B: Suited Manikin Test Apparatus (right half of photo) and Ventilation Test Stand (left half of photo) with RCA 1.0 installed. C: 3D model of RCA 3.0 design.

the systems will operate with an internal atmosphere of nitrogen or air, as they have not been designed for use with 100% oxygen.

The RCA uses a multi-chambered ball valve assembly to switch ventilation loop flow between its two beds (see upper section of the RCA in Figure 4C). While one bed is open to the suit to scrub CO_2 and moisture, the second bed is desorbing to space vacuum. Accelerated life testing was performed on a high fidelity valve assembly for RCA 3.0.[11] The testing was performed for design validation, to mitigate risk of valve failure and to identify any potential unexpected wear internal to the assembly. Because the valve is expected to cycle 40 to 50 times per EVA, and the RCA is rated for 100 EVAs, the valve assembly is expected to experience approximately 5,000 valve cycles over its lifetime. The valve was cycled at an accelerated rate over a period of about 4 months, completing 105,089 cycles, about 21 times the rated design life. Leakage remained within specifications during this period. The valve assembly is currently being dismantled for observation of any wear on critical parts.

B. Variable Oxygen Regulator (VOR)

The objective of the VOR Element is to develop an oxygen-rated, contaminant-tolerant oxygen regulator to control suit pressure with a significantly increased number of pressure set points as compared to the SOA (Table 1). The enhanced performance would facilitate and improve EVA operations and prebreathe protocols, allow regulation of suit pressure to match different vehicle pressures including integration with suit ports, allow for in-suit decompression sickness treatment, minimize or eliminate prebreathe durations prior to an EVA, and provide the flexibility to run variable pressure profiles during an EVA.[5,13,14]

Significant accomplishments since the beginning of the project include (see also schedule in Figure 3):

- Design and fabrication of second generation hardware (VOR 2.0). A total of three units were completed.
- Integration of two VOR 2.0 test articles as part of the Primary and Secondary Oxygen Assemblies of the PLSS 2.0 test article (Figure 5A) and initiation of performance testing as part of the integrated test (Figure 4A). The VOR is expected to be at a TRL of 5 at the completion of this testing.
- Completion of oxygen compatibility testing at White Sands Test Facility (WSTF). The regulator used for this test will be cleaned and refurbished and used for other environments testing (vibration, vacuum, gravity orientation, etc.) later in FY2014, which will advance the maturity of the hardware toward TRL 6.
- Design of third generation (VOR 3.0) hardware. Differences between VOR 1.0, 2.0 and 3.0 are given in Table 2. Fabrication of two VOR 3.0 test articles are expected to be completed during the first part of FY2015. This hardware will be delivered to the AES EVA Systems Project for integration into PLSS 2.5 and later test articles. The technology will be considered at TRL 6 when integrated testing has been completed.

A significant accomplishment this last year was completion of oxygen compatibility testing at WSTF. The testing involved oxygen wetting, simulation of first stage regulator failure, and tolerance to contamination by a mid-weight hydrocarbon (dodecane). The regulator design protected non-metallic and sensitive parts from internal

Table 2. Differences Between First (1.0), Second (2.0) and Third Generation (3.0) Designs of the RCA and VOR Developmental Hardware[11].

	1.0	2.0	3.0
RCA	• Pneumatic spool valve • Subscale • External controller • Operation with air or N_2 • Ambient Lab Environment • Concept lab-scale unit • TRL 3-4	• Motorized ball valve • Full scale • Integrated controller • Operation with air or N_2 • Lab or vacuum environment • Form & fit for PLSS 2.0 integration • TRL 4-5	• Motorized ball valve w/high efficiency actuator • Full scale, optimized size • Improved integrated controller • Oxygen compatible • Flight-like environments • High fidelity brassboard • TRL 5-6
VOR	• Aluminum Body • Bench-top prototype • Rated for nitrogen or air • COTS components • Vacuum/ambient environment • TRL 4	• Monel Body • Improved packaging and size • Rated for 100% oxygen • Contamination tolerant • Improved components • Relevant environment • TRL 5-6	• Monel Body, improved design • Flight-like unit • Rated for 100% oxygen • Contamination tolerant • Flight qualifiable components • Improved controller w/interlocks • Relevant environment • TRL 6

combustion events. Adiabatic heating from sudden pressurization of the interstage volume (from ~200 to ~3,750 psia) following a first stage failure was expected to raise internal temperatures above the autoignition point of potential contaminants, which could cause kindling chain conditions inducing regulator failure. In the first series of tests, the interstage region of VOR 2.0 Unit 3 was subjected to 60 successive pneumatic impacts of 3,750 psi supply pressure of pure oxygen (Figures 6A & 6B). The regulator continued to operate nominally and regulate pressure during and following these events. Dodecane was injected into the regulator to achieve a contamination level of 100 mg/ft^2 followed by 5 high pressure impacts. Injection of dodecane was repeated followed by 5 additional impacts. Again, the regulator continued to operate nominally and regulate pressure during and following these events. Post-test teardown of the regulator confirmed combustion occurred as predicted from analysis, as carbon residue was detected in the filter in front of the second stage regulator. The testing demonstrated the robustness of the regulator design and that it can withstand internal combustion events without failure.

C. Alternative Water Processor (AWP)

The AWP Element's goal is to develop a water recovery system capable of recycling wastewater from sources expected in future exploration missions, including hygiene and laundry water, using an innovative, potentially transformational technology based on natural biological processes. The AWP could ultimately replace the functions of the Urine Processor Assembly and reduce or eliminate the need for the multi-filtration beds used in the Water Processor Assembly on the International Space Station (ISS),[15] thus decreasing the need for consumables as

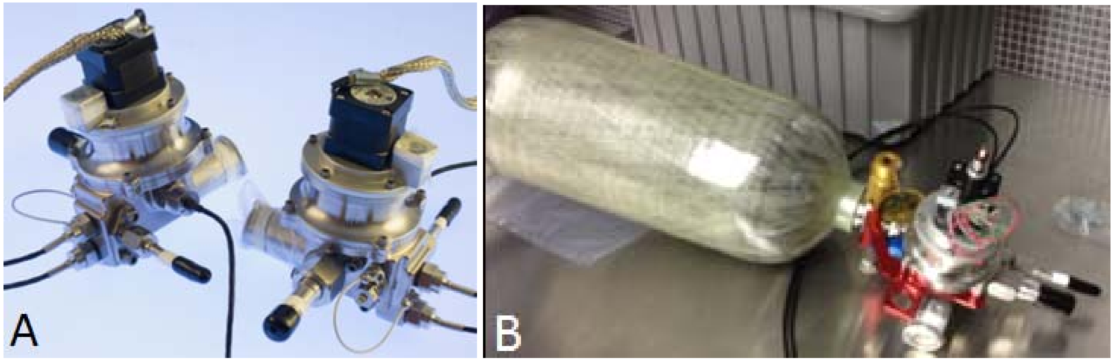

Figure 5. Variable Oxygen Regulator 2.0 Test Articles. A: VOR Units 1 and 2. B: One of the units integrated into a PLSS 2.0 Oxygen Assembly.

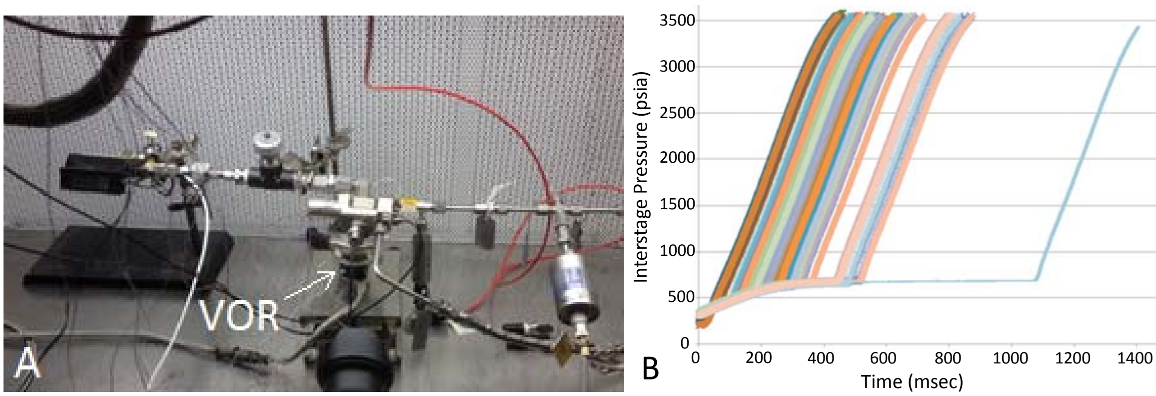

Figure 6. VOR 2.0 Oxygen Compatibility Testing. A: VOR 2.0 Unit 3 mounted in test cell at WSTF, connected to high pressure oxygen system. B: Curve depicts rapid pressure rises during 60 successive pneumatic slams of high pressure oxygen into the interstage section of the regulator. During these events, the pressure rises each occurred in about 360 msec. For impacts with contaminant added, times were purposefully decreased by 50% to 85% to increase adiabatic heating to further encourage combustion.

compared to the SOA. The AWP is being designed to recycle more than 95% of exploration wastewater, including humidity condensate, urine and urine flush, plus hygiene (hand wash, oral, shave and shower) and laundry (Table 3)[16], whereas the ISS water recovery system only treats humidity condensate, urine and urine flush. In addition, in contrast to the ISS WRS, stabilization of the wastewater using harsh and/or toxic chemicals is not required.

At the center of the AWP are two unique "game changing" technologies: 1) a Biological Water Processor (BWP) to mineralize organic forms of carbon and nitrogen;[17,18] and 2) an advanced membrane processor (Forward Osmosis Secondary Treatment (FOST)[19]) for removal of solids and inorganic ions. At the heart of the BWP are four Membrane Aerated Biological Reactors (MABRs), which are targeted to remove >90% of organics, stabilize pH, and convert NH_4^+ to NO_x^- (up to 80%)[17,18] then to N_2. The FOST system, an off shoot of Direct Osmotic Concentration,[20] is a membrane processor that uses a combination of forward osmosis and reverse osmosis in series, that is tolerant to non-volatile organics, solids and fouling.[19] A concept schematic of the AWP is shown in Figure 7. The AWP will be delivered to the AES Water Recovery Project for technology infusion when work is completed.

Significant accomplishments since the beginning of the project include (see also schedule in Figure 3):

- Development of sub-scale and prototype MABRs and their utilization to conduct experimental studies to evaluate wastewater sources, feeding rates, periods of quiescence ("hibernation"), startup methods and

Table 3. Approximate Quantities of Components of "Exploration Wastewater" Used in Alternative Water Processor (AWP) Testing.

Parameter	Units	Ground Based Urine*	Humidity Condensate*	Hygiene					Laundry‡
				Urinal Flush	Hand Wash	Shower	Shave†	Oral	
Nominal load	kg/person/d	2.275	1.15	0.3	1.0	6.0	†	0.2	‡
	kg/4 crew/d	9.1	4.6	1.2	4.0	24.0	0.15	0.8	(28-30 kg)/2
Amount per event	kg/event				0.125	6.0	0.15	0.1	28-30 kg
Frequency of events	Events/4 crew/d				32	4	1	8	0.5‡

*The flight equivalent would be 1.2 kg urine/person/day and 1.95 kg humidity condensate/person/day (4.8 kg urine/per 4 crew/day and 7.8 kg humidity condensate/4 crew/day). For AWP testing, the humidity condensate was added as a concentrate and the makeup water reduced to increase the volume of urine to approximate flight-based urine, which is more concentrated than urine typically collected from ground-based volunteer donors.[16]
†Crewmembers shave once every 4 days (1 event every 4 days per person), equivalent to 1 event per day for 4 crew.
‡One load of laundry is performed every 2 days for 4 crewmembers. 28-30 kg of wastewater is generated per load.

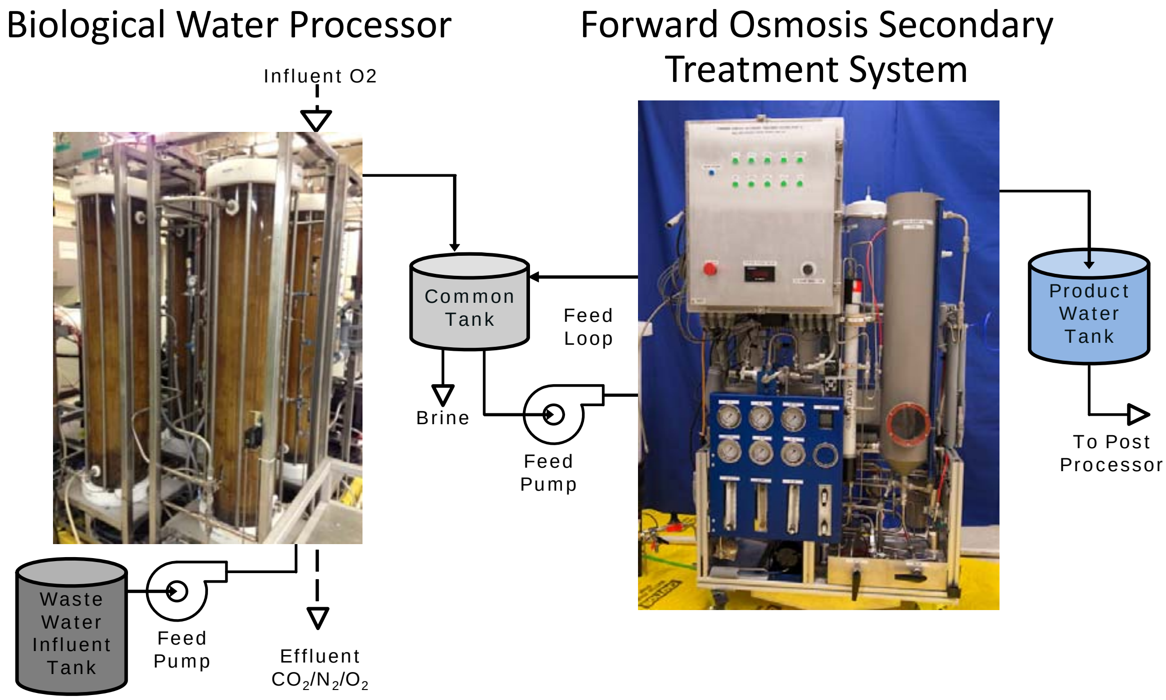

Figure 7. Concept schematic of the Alternative Water Processor. The AWP includes two major subsystems, the Biological Water Processor (BWP) and Forward Osmosis Secondary Treatment System (FOST). The BWP is composed of four Membrane Aerated Biological Reactors and functions to mineralize organic carbon and nitrogen. The FOST includes forward osmosis followed by reverse osmosis processes and functions to remove mineral salts and solids.

reactor design, operations and optimization.[21,22] TRL 4 was achieved at completion of subscale and unit studies.

- Design and fabrication of first-generation FOST hardware and delivery to Johnson Space Center (JSC) for integration into the AWP Breadboard system. Advancement of FOST components include improved forward osmosis (FO) membranes[23,24] and energy-recuperative reverse osmosis (RO) pumps.
- Design and fabrication of the BWP, including four full-scale MABRs. These bioreactors were inoculated April 19, 2013, were brought up to full wastewater loading over a period of 80 days, and have been in operation for approximately 450 days at the time this article was published. The BWPs have averaged 83% organic carbon and 55% ammonium removal (see Figure 8 for example data). Testing uses human

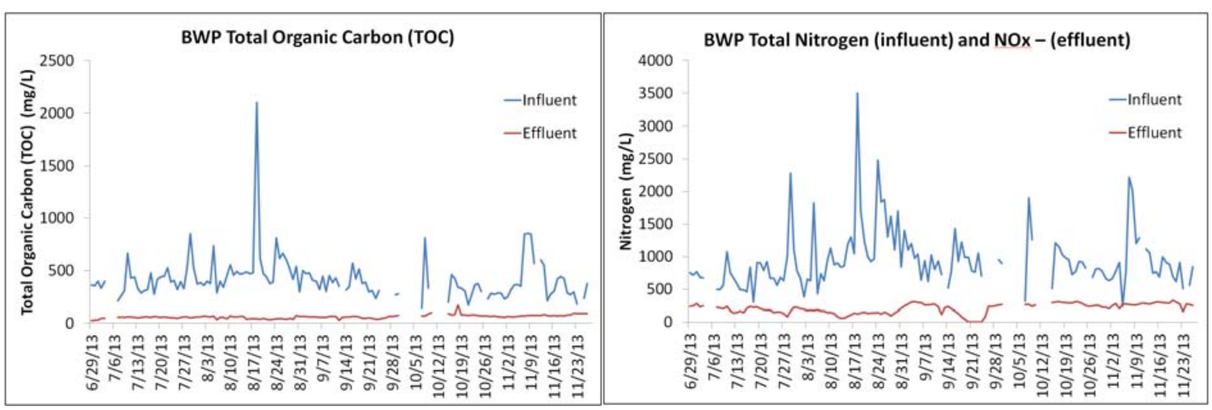

Figure 8. Example data from Biological Water Processor operations. Influent and effluent concentration data for organic carbon and nitrogen. Comparing total nitrogen to nitrogen in nitrate and nitrite forms (NO_x) gives a general measure of the degree of nitrification.

generated wastewater collected by JSC's ground-based Waste Water Collection and Transportation System.

- Integration of the BWP and FOST subsystems into the AWP Breadboard system was initiated May 7, 2013. After 6 runs of the FOST, the average system water recovery rate for the AWP was calculated to be 92%, with maximum achieved rates as high as 98%. Product water quality is suitable for post treatment, similar to that used on the ISS, before it can be considered potable. The AWP will be considered to be at TRL 5 after upgrades are completed to the AWP and additional integrated testing is performed later in FY14.
- Completed development of integrated high-fidelity dynamic models of BWP and FOST components, including MABRs, and FO & RO membrane subsystems. The models were constructed using chemical-process modeling software that simplifies integration, are based on literature parameters and kinetic/transport equations, and account for local acid-base chemistry important to biological and membrane processes. The BWP Model Features: 4 MABRs in series with liquid bypass, 27 biological and chemical species, 7 equilibrium reactions, and includes both biological nitrification and denitrification. The FOST model includes single- or dual-stage RO, 14 chemical species (limited by available membrane rejection data), includes 3 equilibrium reactions, can be used to predict salt solubility limits at high water recovery and can be used to test/verify control strategies.

D. High Performance Extravehicular Activity Glove (HPEG)

The HPEG Element is a new activity within NGLS initiated at the start of FY2014 and planned as a 3 year technology development task. The overall objective is to develop advanced EVA gloves for future human space exploration missions and generate corresponding standards by which progress may be quantitatively assessed. The glove prototypes that result will be infused into the AES EVA Systems Project for evaluation in an integrated test for the next generation spacesuit.

Exploration missions significantly differ from the ISS. Whereas the ISS external environment is relatively pristine, dust and other foreign debris on all exploration missions can easily migrate through protective glove outer layers creating a high potential for loss of hardware and increase risk to crew. On the ISS, spare gloves can easily be resupplied and EVA frequency is less than 24 hours per quarter. In comparison, exploration design reference missions anticipate up to 24 hours of EVA per week, and have limited or no resupply. Durability, performance and injury risk are much more of a concern. Issues of mobility, fit, and durability must be addressed in a systematic manner that incorporates new technologies and manufacturing techniques to meet the performance challenges of exploration missions. Critical key performance parameters for HPEG include the following (Table 1): 1) Enable hand mobility comparable to 60% of bare handed capability when wearing the complete glove assembly pressurized to 4.3 psid (functional at pressures as high as 8.4 psid). 2) Maintain structural integrity after completion of cycle testing in non-pristine environment for the equivalent of 50 EVAs.

HPEG is divided into three sub-task areas: Technology Development, Standards Development, and Integrated Glove Prototypes.

Technology Development The aim of this sub-task is to provide glove vendors with performance metrics for emerging technologies that show promise for improving glove performance with respect to mobility, durability, and comfort and build upon previous NASA experience and technology investments to reduce both cost and schedule for the overall integrated glove prototype contracts. The technology focus areas include flexible aerogel, dust management, in-glove sensors, and robotic grip assist. A series of testing and/or analysis will be conducted for each focus area to characterize the technology readiness for implementation into an exploration glove prototype.

Standards Development There are no standards for acceptability and testing to assess glove development progress and performance of new designs. Additionally, uniform test methods will increase the value of hardware developed by different institutions. Standards to be developed will cover human-glove performance, glove durability in exploration environments and injury assessment. Specific aims of the Standard Development sub-task are as follows:

- Refine and validate methodologies to standardize processes for evaluating the performance of new glove technologies in goal areas including mobility, durability, and injury potential (Figure 9).
- Perform manned suited evaluations to document standard procedures for and results of manned strength and mobility of Phase VI and new glove prototypes
- Review injury reports in conjunction with sizing data to identify trends and causation with respect to injury; establish a method for assessing new glove designs against findings.

- Define standards to be used for assessing materials properties of existing and future glove designs to enable rapid assessment of progress/potential.
- Publish validated methodologies and disseminate to current and future glove vendors to increase synergy across the industry

Integrated Glove Prototype This sub-task will incorporate the findings of the Technology Development and Standards Development sub-tasks to generate human-rated high-performance EVA glove prototypes that show improved performance with respect to the SOA gloves in the areas of mobility, durability, and injury avoidance. A statement of work and supporting contractual information will be generated in FY2014 with contract award in early FY2015, subject to availability of funding. Glove prototypes are to be delivered in FY2016 with NASA in-house testing later that year.

Figure 9. Evaluating protocols for assessments of glove mobility. Test subject in pressurized suit performing "Pin" task.

E. Advanced Oxygen Recovery (AOR)

The chief goal of the AOR Element is to develop technologies that allow for increased recovery of oxygen from CO_2 as compared to the SOA. Currently the Carbon Dioxide Reduction System (CRS) in use on the ISS incorporating a Sabatier reactor, is capable of recovering not more than 50% of the oxygen from metabolic CO_2 because about half of the hydrogen used in the reaction is vented as methane,[25] rather than yielding additional water. Increasing the recovery of this oxygen could be accomplished by a variety of alternative solutions, including but not limited to Bosch CO_2 reduction, utilizing carbon formation reactors or methane pyrolysis to recover additional hydrogen from the CRS, and architectures that incorporate CO_2 electrolysis or co-electrolysis. Due to limitations in funding, this element was de-scoped during the first year of NGLS into a formulation task aimed at defining and proposing new technology investments for future fiscal years. Toward this end, a NASA Research Announcement was released in April 2014 to solicit proposals in this technical area. Given the availability of funding, it is anticipated that multiple awards will be funded in early FY15.

Beginning in FY2013, however, a limited amount of funding was made available to support a low-level of activity at NASA's Marshall Space Flight Center (MSFC) to further the development of Bosch technology. Work has focused on development of a Series-Bosch (S-Bosch) oxygen recovery system.[26] S-Bosch is based on the Bosch process, which can theoretically recover 100% of the oxygen from metabolic CO_2. All reacted hydrogen is recovered in the water product, and elemental carbon is the only byproduct. Designs for an S-Bosch test stand incorporate two catalytic reactors in series including a Reverse Water-Gas Shift (RWGS) Reactor (Figure 10, left) and a Carbon Formation Reactor (CFR). In late FY2013, fabrication of system components, with the exception of a

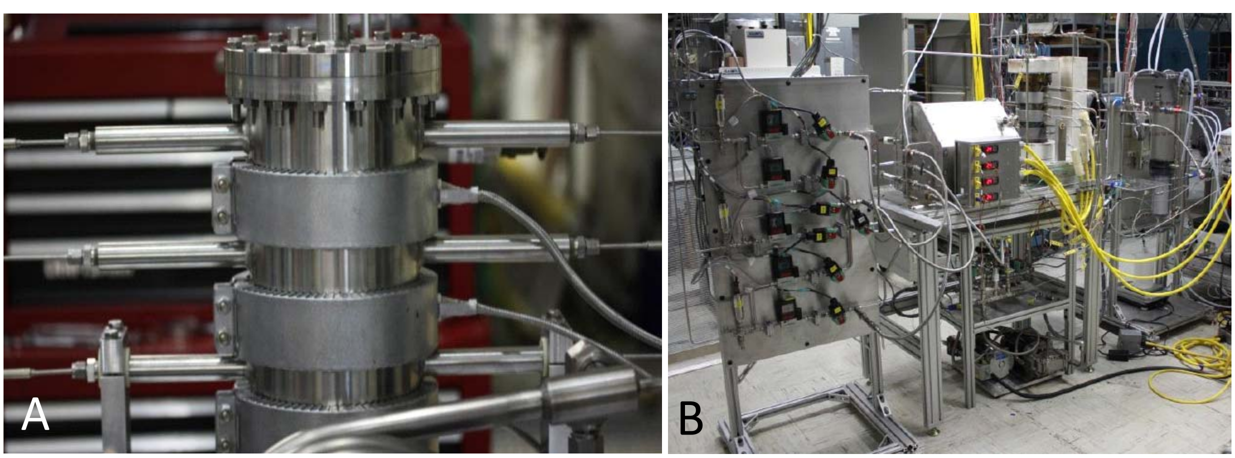

Figure 10. A: Reverse Water Gas Shift Reactor. B: Series-Bosch Test Stand.

CFR, and assembly of the test stand was completed (Figure 10, right). In FY2014, stand-alone testing of the RWGS reactor was completed to compare performance with design models. Lunar and Martian regolith simulants were evaluated to serve as catalysts to eliminate the need for catalyst resupply, a major limitation of Bosch technology to date. Lastly, a study was conducted to explore manufacturing bricks from spent regolith catalysts for use in planetary surface construction. For additional information and detail, please see papers by Abney, *et al.*[26,27,28]

VI. Future Work

Three major NGLS technology development tasks will be ending in FY2014 after 3 years of investment: VOR, RCA and AWP. These technologies will be infused by Advanced Exploration Systems Projects further maturation. HPEG will be continuing for up to 2 more years, entering a phase of advanced glove design and fabrication. The AOR Element will be formally started, moving from formulation to implementation. Given availability of funding, multiple Phase I awards may be made in early FY2015 based on a solicitation that was released in FY2014. After approximately 15 months, the funded work will be competitively down-selected to up to 2 Phase II awards for development of prototype hardware.

Other technical areas are under consideration for investment. A major challenge identified for Environmental Control and Life Support (ECLSS) Water Recovery and Management is " Increase overall water recovery percentage" with the milestone of achieving 98% recovery in the 2015 to 2019 timeframe as detailed in the Human Health, Life Support and Habitation Systems Roadmap[1]. This level of closure can only be achieved if water is recovered from waste brines generated by spacecraft water recovery systems. A Technical Interchange Meeting (TIM) was held in January 2014 on the topic of water recovery from brines produced by primary water processors (distillation, membrane separation, and biological treatment) to increase loop closure of human wastewater recovery systems.[29] Its goal was to develop and capture a comprehensive understanding of the issues and needs in order to better define and enable future brine processing technology development efforts. Based on findings from this workshop NGLS is formulating an additional technology development Element to be brought forward to STMD for consideration for investment.

The NGLS project will continue to seek unique gap-filling technologies that will enable critical capabilities for spacecraft cabin and EVA systems to extend human presence beyond low-Earth orbit into the solar system. Selected technologies must be focused on increasing affordability, reliability, performance and vehicle self-sufficiency while decreasing mass and enabling long duration exploration.

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