46th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria ICES-2016-103

Using the International Space Station (ISS) Oxygen Generation Assembly (OGA) Is Not Feasible for Mars Transit

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A review of two papers on improving the International Space Station (ISS) Oxygen Generation Assembly (OGA) shows that it would not save substantial mass on a Mars transit. The ISS OGA requires redesign for satisfactory operation, even for the ISS. The planned improvements of the OGA for ISS would not be sufficient to make it suitable for Mars, because Mars transit life support has significantly different requirements than ISS. The OGA for Mars should have lower mass, better reliability and maintainability, greater safety, radiation hardening, and capability for quiescent operation. NASA's methodical, disciplined systems engineering process should be used to develop the appropriate system.

Nomenclature

AAA	=	Avionics Air Assembly
ACTEX	=	Activated Carbon/Ion Exchange
DI	=	Deionizing
dP	=	delta Pressure
ECLSS	=	Environmental control and Life Support System
ESM	=	Equivalent System Mass (ESM)
H2	=	Hydrogen
ISM	=	Independent Shutdown Monitor
ISS	=	International Space Station
IX	=	Ion Exchange
LCC	=	Life Cycle Cost
LFL	=	Lower Flammability Limit
MDM	=	Multiplexer/Demultiplexer
MTBF	=	Mean Time Before Failure
NASA	=	National Aeronautics and Space Administration
O, O2	=	Oxygen
OGA	=	Oxygen Generation Assembly
OGS	=	Oxygen Generation System
ORU	=	Orbital Replacement Unit
PSM	=	Power Supply Module
R&R	=	Remove and Replace
RSA	=	Rotary Separator Accumulator
SSF	=	Space Station Freedom
SOA	=	State of the Art
TOC	=	Total Organic Carbon
WRS	=	Water Recovery System

I. Introduction

THIS report reviews two recent papers that investigate how the Oxygen Generation Assembly (OGA) that is now on the International Space Station (ISS) can be used for future long duration missions and the journey to Mars.

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Life support systems that recycle water and oxygen for long duration missions were first developed in the Apollo era for future missions. The current Environmental Control and Life Support System (ECLSS) design that has been operational on ISS for several years was originally developed for Space Station Freedom (SSF) before the collapse of the Soviet Union. A similar system is expected be used on future long duration missions. The question here is, "Can we use the ISS OGA for Mars?" The reviewed papers are optimistic.

The first reviewed paper by Takada, Ghariani, and Van Keuren titled "Advancing the Oxygen Generation Assembly Design to Increase Reliability and Reduce Costs for a Future Long Duration Mission," states that "Lessons learned from operating the ISS OGA have led to proposing incremental improvements to advance the baseline design for use in a future long duration mission." And, "A future OGA system for exploration should logically be based on the state of the art (SOA) ISS OGA. Since the ISS OGA has proven to be extremely safe and reliable over eight years of operation, it will provide an excellent foundation for the design of a future system. However, certain incremental improvements based on lessons learned should be considered." (Takada et al., 2015-115)

The second paper by Bagdigian, Dake, Gentry, and Gault titled, "International Space Station Environmental Control and Life Support System Mass and Crewtime Utilization In Comparison to a Long Duration Human Space Exploration Mission," takes a more tentative initial approach. It says, "An important question … is how well suited is the ISS ECLSS suite of technologies to meeting the needs of future missions?" These authors conclude that, "With several readily apparent exceptions, … OGS equipment has been shown to be capable of achieving operational lifetimes on the order of those needed to support such (long duration) missions." (Bagdigian et al., 2015-094)

II. The International Space Station (ISS) Oxygen Generation Assembly (OGA)

The function of the ISS OGA is to convert potable water from the ISS Water Recovery System (WRS) into oxygen and hydrogen. The oxygen is sent to the crew cabin, and the hydrogen is either vented to space or used to produce more water.

A. OGA description

Figure 1 is a simplified schematic of the OGA taken from Takada et al., 2015-115.

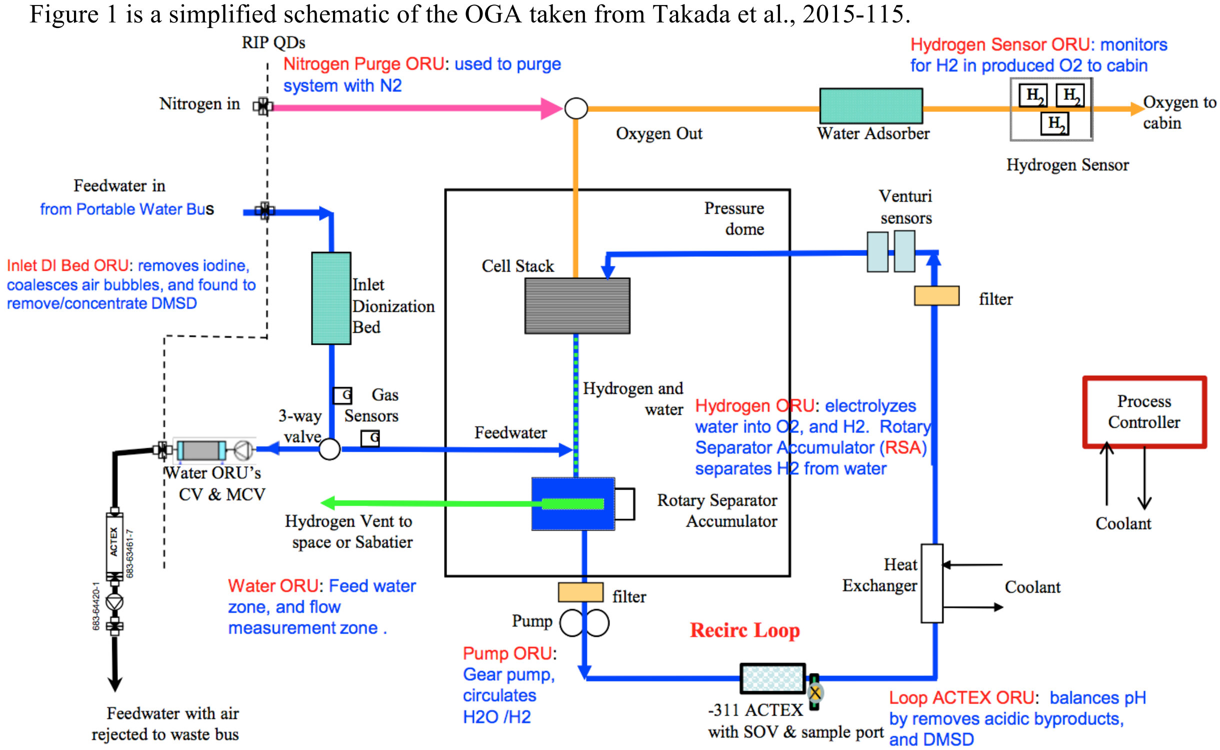

Figure 1. Simplified OGA schematic. (Takada et al., 2015-115)

B. OGA Orbital Replacement Units (ORUs)

The OGA uses the ISS maintenance and repair approach. Orbital Replacement Units (ORUs) are stored on board to replace failed units. The OGA ORUs are listed in Table 1.

Table 1. Oxygen Generation Assembly (OGA) Orbital Replacement Units (ORUs

#	ORU designation	Full name	Description
1	Hydrogen ORU	Hydrogen Pressure dome	Electrolysis cell stack, Rotary Separator Accumulator, pressure dome
2	Controller	Process Controller	Control and communication
3	O2 ORU	Oxygen Outlet	Removes water in oxygen output to cabin
4	H2 Sensor ORU	Hydrogen Sensor	Measures hydrogen in oxygen output to cabin
5	Pump ORU	Pump	Water and hydrogen loop recirculation pump
6	Inlet DI Bed ORU	Inlet DI Bed	Feedwater iodine removal deionization bed
7	Nitrogen Purge ORU	Nitrogen Purge	Purges system of hydrogen and oxygen
8	PSM	Power Supply Module	Current to cell stack
9	ACTEX	Loop ACTEX	Activated Carbon/Ion Exchange - recirculation loop deionization bed
10	Water ORU	Water	Feed water flow control

"Most of the OGA ORUs are run to failure except for the calibration life limited Hydrogen Sensor ORU and the mixed-resin containing ORUs (Inlet DI Bed and ACTEX) which are trended for water throughput and return water quality to determine the Preventative Maintenance (PM) replacement intervals." (Takada, et al., 2015-115)

III. The OGA analysis by Takada, Ghariani, and Van Keuren

The paper by Takada, Ghariani, and Van Keuren summarizes the failure history, repairs, lessons learned, and the past and planned future redesign of the ISS OGA. (Takada et al., 2015-115)

A. Overview of Takada et al., 2015-115

The major sections of the paper by Takada et al. are: History of the ISS OGA, Description of the ISS OGA, Lessons Learned from ISS OGA, Requirements for a Long Duration Exploration Mission, Proposed Incremental Improvements, and Proposed Next Generation OGA Architecture.

The Oxygen Generation System (OGS) was launched in July 2006 and the OGA was activated in July 2007. The accumulated OGA operating time in early 2015 was 33,392 hours, only 133 of which were on the ground before launch. The Lessons Learned from ISS OGA includes discussions of Cell Stack Failure in 2010, Hydrogen Sensor Drift, and Need for Day/Night Cycling. A historic timeline of major OGA events is provided. The Proposed Incremental Improvements that are justified in detail include Replacing the Cell Stack Membrane, Deleting the Nitrogen Purge Equipment, Replacing the Hydrogen Sensors with a Recombiner, Deleting the Wastewater Interface, Replacing the Hydrogen Dome with a Shroud, and Downsizing the Power Supply Module.

B. Major OGA failure and maintenance events in Takada et al.

Figures 5 and 6 of (Takada et al., 2015-115) show the timeline of all the significant OGA events, except that the scheduled Hydrogen Sensor ORU replacement is shown in Figure 7. (Takada et al., 2015-115). There are 35 non-H2 sensor events in Figures 5 and 6 and eight H2 sensor ORU remove and replacements (R&Rs) in Figure 7.

The failure events can be organized in groups. Five different event categories were identified by Takada et al. These groups are Loop filter dP issues, Low pH issues, High TOC events, H2 sensor, and Other. Fourteen new event groups can be identified. These new groups and their counts are AAA filter (4), ACTEX (4), Calibration (1), Cell stack (4), dP sensor (2), H2 sensor R&R (8), H2 sensor calibration (2), Limit exceed (3), Loop filters (6), Pressure test (2), Pump (1), Seal (1), TOC 1 (3), and TOC 2 (2). The new event groups were defined based on the five Takada et al. event categories and other information in Takada et al. All events are assigned to a group.

1. Filter and Cell stack events

The first group of Takada et al., Loop filter dP issues, corresponds to the new group of Filter. The OGA recirculating loop pressure increased, apparently because the filters were clogged, and the filters and the Water ORU were replaced, ultimately using new design filters. This problem apparently had the same cause as the second group of Takada failure events.

The second group of Takada et al., Low pH issues, corresponds to the new group of Cell stack. Initially low pH was noted in the OGA recirculating loop, and this produced corrosion products that clogged the loop filters. The apparent failure mechanism was as follows: the electrolysis cell membranes typically degrade, they produce acid and low pH, this caused corrosion that blocked the filters and contaminated the cell membranes, this increased their resistance, driving up the voltage to the shutdown limit. This problem was cured by adding the deionization bed into the loop to remove the acid and contaminants and by replacing the Hydrogen ORU.

The two new failure groups, Filter and Cell stack, have the same cause, cell membrane degradation producing contaminants and acid. These two failure groups include 10 of the 43 failures. These all occurred during the first 20 months of the 70 month record. The major failure event during OGA operations on ISS was the Cell stack failure. Initial attempts to treat the Loop dP symptom let to use of new filters. Finally, "a deionization bed was retrofitted in the recirculation loop in 2011." (Takada, et al., 2015-115)

This is a classic case of a high initial failure rate, often called "infant mortality." A design oversight led to a cluster of common cause failures that could only be cured by a design modification. Takada et al. noted that, "Published literature for fuel cell technology identified that there is a known chemical degradation of the cell membrane polymer chain end groups during normal operation." Ground testing before flight was limited.

The third group of Takada et al., TOC, is split into two new groups, TOC 1 and TOC 2, spread in time. The fourth Takada et al. group, Other, is assigned into nine new groups.

2. H2 sensor events

H2 sensors R&R events were separately identified by Takada et al. and form a new event group. The H2 sensors are triple redundant. They had excessive drift that was accommodated by an operational procedure change. High sensor readings were tolerated in one of the three sensors. Because of this, H2 sensors R&R was not necessary at times other than at the scheduled intervals.

Figure 2 plots the time averaged cumulative failure rate, N(t)/t, for all the failure and maintenance events. The event rates for the combined Filter and Cell stack group and for the H2 sensor group are also plotted.

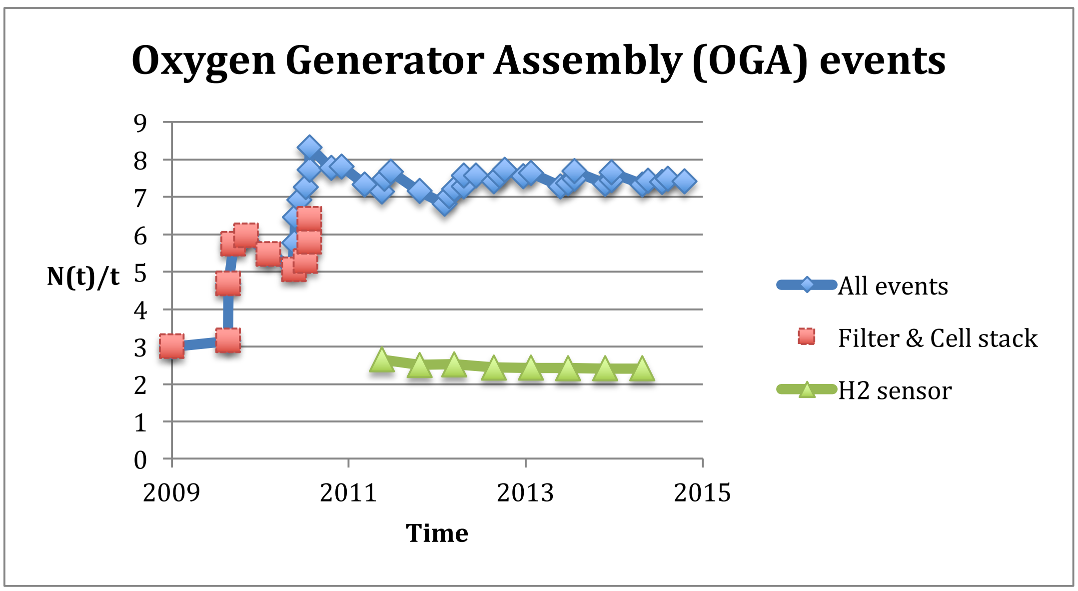

Figure 2. The time averaged cumulative failure and maintenance rate, N(t)/t, for all the events, for the combined Filter and Cell stack group, and for the H2 sensor group.

After an initial increase nearly all due to the combined Filter and Cell stack event group, the overall cumulative average event rate remains constant at about 7 or 8 per year for the next four years. The H2 sensor R&R events occur at a constant rate, every 150 days, a little more than two per year.

3. Events other than Filter and Cell stack and H2 sensor

Figure 3 plots the number of failure and maintenance events each year for the combined Filter and Cell stack groups, 10 events, the H2 sensor group, 8 events, and all other failures and maintenance,11 groups with 25 events.

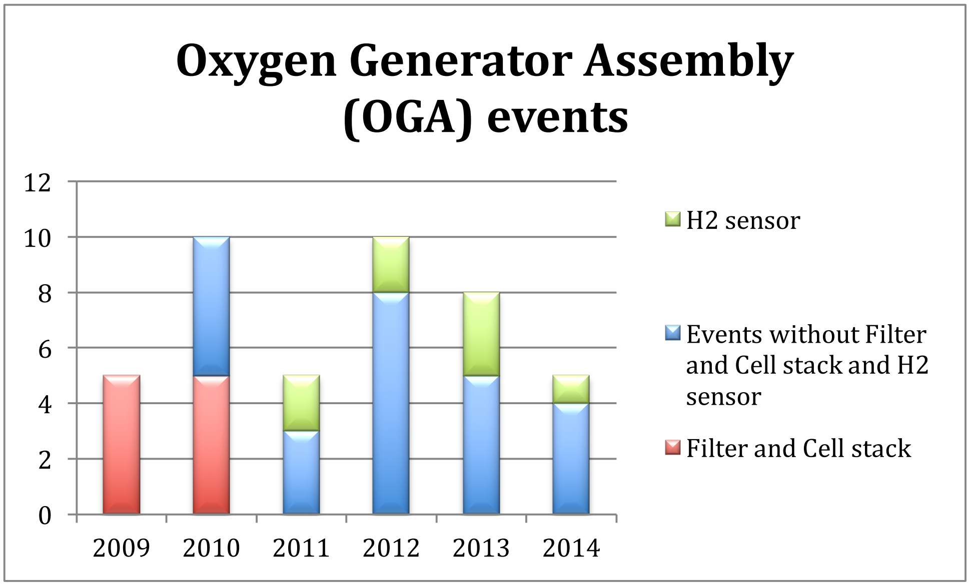

Figure 3. The number of failure and maintenance events each year without Filter and Cell stack and H2 sensor, for the combined Filter and Cell stack group, and for the H2 sensor group

The early Filter and Cell stack problems were very significant and resulted in adding the Loop ACTEX ORU and replacing the Water ORU and Hydrogen ORU. After these OGA problems were corrected and the OGA restored to normal operation, other failure and maintenance events occurred at a declining rate. The H2 Sensor drift is a significant problem but did not result in unplanned maintenance. The OGA does not show the noticeable reliability growth or failure rate reduction that sometimes occurs when infant mortality is cured by discovering and repairing design errors.

There are 25 events in the 11 groups other than Filter and Cell stack and H2 sensor R&R. The event groups, number in each group, and event description are shown in Table 2.

Table 2. Failure and maintenance events other than Filter and Cell stack and H2 sensor

Event group	#	Event description
ACTEX	4	Scrub, install, R&R
Calibration	1	Recirculation loop temperature update
dP sensor	2	Fails, drifts
H2 sensor calibration	2	Calibration changed, related to H2 sensor problem
Limit exceed	3	Different limits - loop pressure, feed water, gas
Pressure test	2	Vent dome pressure test
Pump	1	Pump ORU failed, possibly part of Loop filter and Cell stack problem
Seal	1	Oxygen outlet seal taping
TOC 1	3	TOC climbs due to feed water and drops
TOC 2	2	TOC climbs due to feed water and drops after IX bed R&R

Many of the events in Table 2 are related to the Filter and Cell stack and H2 sensor problems. The changes in H2 sensor calibration are related to the H2 sensor drift problem. The Pump ORU replacement may be related to the Loop filter and Cell stack problem. The ACTEX was added to solve the Loop filter and Cell stack problem. Most of the other events are cleaning or sensor issues, but the twice occurring high TOC is a external cause of concern. The high rate of events reflects a need for repair, maintenance, and crew time that should be mitigated if possible.

C. Planned OGA incremental improvements

Many additional improvements to the OGA are suggested. “The proposed improvements include replacing the cell stack membrane material, deleting the nitrogen purge equipment, replacing the hydrogen sensors, deleting the wastewater interface, replacing the hydrogen dome, and redesigning the cell stack power supply. … Additionally, a redesigned system architecture will be proposed.” (Takada, et al., 2015-115) These incremental improvements are so many that they approach a redesign, but the guiding concept is that the next generation OGA should be based on the original ISS OGA and not a clean sheet new design. The proposed improvements are listed in Table 3.

Table 3. Improvements proposed for the OSS OGA.

#	Change	ORU	Reason
1	Cell stack membrane replacement	Hydrogen	The original cell stack membrane is no longer made.
2	Delete the nitrogen purge equipment	Nitrogen Purge	Nitrogen purging may not be necessary. The nitrogen purge equipment weighs about 50 lbs.
3	Replace hydrogen sensors	H2 sensor	The H2 sensors drift and have a calibration life of only 150 days. A hydrogen-oxygen recombiner is suggested.
4	Delete the wastewater interface	Water	Diverting feed water with oxygen bubbles away from the cell stack may not be necessary.
5	Replace the hydrogen dome	Hydrogen Pressure dome	It may be possible to use a removable shroud instead of a fixed dome.
6	Downsize the PSM	PSM	A lower oxygen requirement would allow the PSM to be downsized.
7	Loop water refresh	Refresh (new)	Allow reducing high TOC.
8	Disable Independent Shutdown Monitor	Controller	For troubleshooting and workarounds.
9	Relocate filters	Most	Embedded filters require replacement of an entire ORU.
10	Add thermal expansion capability and flex hoses	Most	Now thermal expansion devices must be used during maintenance.
11	Disable fluid connect keying		Keying prevents flexible response to contingencies.

These changes are described further in (Takada, et al., 2015-115). The second through seventh improvements are major changes in the ISS OGA system design concept. The last four changes are intended to reduce repair, maintenance, and crew time and would apply to any similar liquid handling space system.

IV. Proposed next generation OGA architecture

Table 4 indicates which of the OGA ORUs are proposed to be added, deleted, or redesigned.

Table. 4. OGA ORUs to be added, deleted, or redesigned.

#	ORU designation	Change
1	Hydrogen ORU	Shroud instead of dome, new membrane
2	Controller	New sensors and control, disable ISM
3	O2 ORU	
4	H2 Sensor ORU	O2-H2 recombiner instead of sensor
5	Pump ORU	
6	Inlet DI Bed ORU	
7	Nitrogen Purge ORU	Deleted
8	PSM	Downsize to half power
9	ACTEX	Added after ISS failure
10	Water ORU	Delete wastewater interface
11	Water refresh ORU	New

The OGA originally had nine ORUs and is proposed to have ten. The ACTEX was added after the ISS Cell stack failure. A new Water refresh ORU is proposed. The Nitrogen Purge ORU is planned to be deleted. Table 4 shows that all but three of the eleven listed ORUs will be significantly changed in the proposed next generation OGA architecture. The proposed future OGA schematic is much simpler than the current one. Figure 4 is the proposed schematic of a future OGA taken from Takada et al.

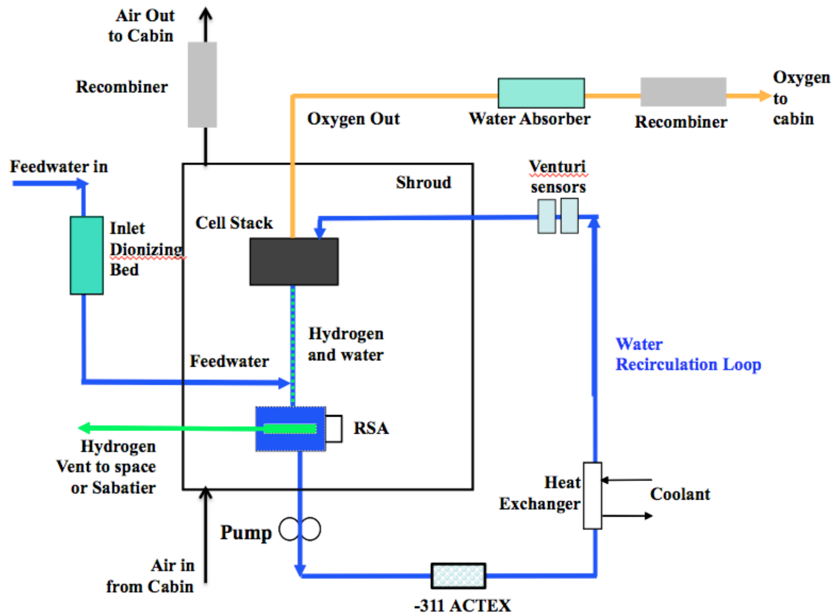

Figure 4. Proposed schematic of a future OGA. (Takada et al., 2015-115)

V. Advancing the OGA for ISS and for future long duration missions

The proposed development of the OGA by Takada et al. will be considered with regard to two very important OGA objectives that should be distinguished. The first objective is to improve the ISS OGA for better performance and easier maintenance on the ISS. The second is to advance the ISS OGA baseline design for use on a future long duration mission.

A. Improving the ISS OGA for use on ISS

Clearly the lessons learned from operating the ISS OGA have provided deep engineering knowledge and important practical suggestions for improving performance, reducing crew maintenance time, improving reliability, and reducing resupply mass from Earth. Some of the suggested improvements can be easily implemented on ISS, such as deleting the nitrogen purge and the wastewater interface. Other improvements would be implemented in new operational hardware or spares.

B. Improving the ISS OGA for use on a future long duration mission

While the improvements of the ISS OGA in system complexity, mass, reliability, maintenance, and resupply will be very useful for future missions, these future missions will have new challenges in addition to those of ISS. The paper by Takada et al. points out that the proposed improved future OGA will be much better suited for a future long duration mission. It will increase reliability and reduce the costs, system weight, crew maintenance time, and resupply mass. “Future deep space long duration missions will not likely have logistics resupply capability from Earth to provide spare ORUs. Therefore, it will become important to allow the crew flexibility to access and repair internal components of complex ORUs.” (Takada et al., 2015-115) The use of filters will be minimized. Filters will be located to be easily inspected, replaced, or cleaned. The hydrogen dome will be replaced by a shroud for easier access and repair of internal components.

Takada et al. mention that, “The general requirements for a future long duration exploration mission will likely be different from those that influenced the ISS OGA design.” They consider two specific different requirements, the oxygen production rate and the procedures for safe management of hydrogen and oxygen. Fewer crew and the expected continuous power availability on a future mission will allow the oxygen production rate to be reduced by more than half. Some specific systems and procedures established to ensure safe management of hydrogen and oxygen are proposed to be eliminated in future systems. These include the hydrogen dome, the nitrogen purge, and the wastewater interface. “Over the many years of operating the ISS OGA, valuable experience and understanding has been gained relating to the safe management of hydrogen and oxygen. Through careful analysis and testing, some of the conservatism in the design can be reduced without adding appreciable risk.” (Takada et al., 2015-115)

C. Problems using or adapting the ISS OGA for future missions

Past discussions of Mars missions have usually assumed that the life support systems will be similar to ISS but redesigned as needed for the new mission. System developers tend to prefer a fresh start. There have been extensive long term efforts to develop life support systems that improve on ISS for future missions. Being able to use a system very similar to the ISS OGA for exploration missions and Mars would maximize the use of ISS experience and could save time and money, but there are many problems on this path.

1. The ISS OGA has current problems

Failure and maintenance events continue to occur and maintenance require spare ORUs and crew time.

2. The ISS OGA has extensive planned redesign

The need to correct problems and make improvements has led to proposing significant redesign. Changes that cure one problem may create additional problems. The suggested changes in the planned future ISS OGA are so extensive that it seems reasonable to also consider a similar clean sheet design.

3. The ISS OGA requirements differ from the Mars OGA requirements

There are many similarities between ISS and Mars OGA requirements, so the designs will be similar. There are also some important differences, so the optimum designs will probably differ.

The major difference is that life support in deep space must be considerably more reliable than on ISS, where emergency resupply or quick return are possible. Another related problem noted by Takada et al. is that the ORU maintenance approach is unsuitable for deep space with ORU's as large and complex as those now provided for ISS. Takada et al. suggest removing the hydrogen dome to facilitate component repair, however they do not specifically analyze reliability or develop a deep space repair and maintenance concept. Takada et al. also note the different lower quantity of oxygen required. A Mars transit OGA would also require the ability for quiescent waiting in Mars orbit and hardening for deep space radiation. A Mars surface OGA would be able to take advantage of Mars gravity and possibly depend on oxygen obtained from the Mars atmosphere. (Jones et al., 2014-074)

4. The ISS OGA is designed for ISS not Mars

A real hardware system such as the ISS OGA cannot be optimized for two different missions with different requirements at the same time. This problem is most strongly demonstrated by the different levels of OGA reliability thought to be needed for crew safety. Both the ISS and Mars OGAs must not endanger the crew. The ISS OGA poses little risk to the crew even with the current failure and maintenance events, for several important reasons. The large volume of the ISS and the oxygen storage tanks provide a large oxygen buffer. The Russian life support system includes an alternate OGA. OGA ORUs are stored onboard and if used can be resupplied fairly quickly. If an OGA failure leads to an oxygen emergency, the crew can immediately return to Earth.

Because a Mars mission cannot be easily resupplied, and because a Mars crew cannot return ahead of a schedule determined by planetary orbits, it is usually understood that a Mars life support system should have much higher reliability, maintainability, and reparability than a system on ISS. The level of reliability required for Mars will depend on the overall design for crew safety, which could include abort options, stored supplies, and backup systems.

Although reliability was important in technology selection, the ISS ECLSS was not designed for unnecessarily high reliability. New valves were selected for low mass rather than heavier ones with demonstrated reliability. Integrated systems such as the OGA were tested only briefly before launch, rather than having their life demonstrated. Since high reliability was not the priority in ISS OGA design, it seems that its reliability can be improved relatively easily. The reliability approach should be coupled with a new deep space repair and maintenance concept that replaces the ISS ORU approach.

5. The future ISS OGA will have fewer safety systems

The hydrogen dome, the nitrogen purge, and the wastewater interface that were provided to ensure the safe management of hydrogen and oxygen seem excessive and will be removed. This will reduce system mass, complexity and logistics resupply. It is difficult to determine how much safety is required, how safe a system is, and what safety improvements are more cost-effective. But we need more safety for Mars than for ISS, not less.

Experience and the understanding it provides are very useful, but they are poor guides in assessing the probability of accidents that have not recently occurred. The three Russian Elektron oxygen generators on board ISS were "plagued with problems" in the mid 2000's. (Wikipedia, ISS ECLSS) NASA's tragic experience with Challenger should remind us that it is easy to mistakenly assume that things that are going well will continue to go well. We cannot be certain that the current ISS OGA, even with all its safety systems, will not have any problems.

Funding, developing, testing, and flying the future OGA proposed by Takada et al. would be very worthwhile. The Mars OGA could easily differ from the ISS OGA. The design of the OGA for Mars should be based on extensive risk, hazard, and safety analysis.

D. Overall systems engineering and management guidance is lacking

Takada et al. provide excellent understanding of the OGA hardware, its history, and its needed improvements. They have begun to take a conservative, sound approach to advancing the OGA for future exploration missions. But more needs to be done. Standard NASA systems engineering and development project planning would include requirements definition, alternate concept development, and trade-offs based on analysis of performance, cost, risk, reliability, maintainability, etc. Even in the rare case where an off-the-shelf, flight proven solution is available, the systems engineering process should be used to ensure it is best.

Engineers appropriately focus on the important technical details involved in developing and improving the performance of their hardware. Nothing is more necessary, but advancing technology beyond the development laboratory also depends on a myriad of systems factors. Development engineers directly feel the usual unwelcome constraints on mass, volume, power, current budget, and schedule. They may postpone or even omit considering maintainability, operability, reliability, and overall cost unless reminded of overall mission requirements by systems engineering or management. The next paper to be reviewed provides an overview perspective on advancing the OGA for a long duration mission.

VI. The OGA analysis by Bagdigian, Dake, Gentry, and Gault

The paper by Bagdigian, Dake, Gentry, and Gault titled, "International Space Station Environmental Control and Life Support System Mass and Crewtime Utilization In Comparison to a Long Duration Human Space Exploration Mission," considers the question "(H)ow well suited is the ISS ECLSS suite of technologies to meeting the needs of future missions?" The paper surveys the maintenance history of the ISS Water Recovery System and the OGA. The equipment mass used and the achieved hardware operating lifetimes were determined to help assess cost and reliability for a Mars mission. (Bagdigian et al., 2015-094)

A. Overview of Bagdigian et al., 2015-094

The paper by Bagdigian et al. describes Mars Design Reference Architecture 5.0, the ISS maintenance data that is tracked at the ORU level, the ISS Water Recovery System, and the ISS OGA. The sections on the Water Recovery System and the OGA include schematics, descriptions of operation, a figure on the life cycle system mass used and material produced, a figure on the maintenance events and crew time used, and figures comparing the OGA operating life history to a 1,000 day mission duration target.

B. The OGA removal and replacement and maintenance events from Bagdigian et al.

Bagdigian et al.'s figure 10 shows the life cycle system mass used for the OGA and oxygen produced, and it tracks the timeline of the ORU Remove and Replace (R&R) events that increase the total OGA mass utilized. Their figure 11 shows the OGA maintenance events and accumulates the crew time used. (Bagdigian et al., 2015-094)

1. The OGA removal and replacement events from Bagdigian et al.

Bagdigian et al.'s figure 10 tracks the increasing mass utilized to keep the OGA operating. The only events are R&R, Remove and Replace. There are 20 H2 Sensor replacements, 8 ACTEX replacements, 2 FSE replacements, and one each of Water (H2O) ORU, Pump ORU, and H2 ORU, replacements. There are 33 total R&Rs. Figure 5 plots the number of OGA Repair and Replace (R&R) events each year for the H2 sensors, 20 events, the ACTEX, 8 events, and other R&R, 5 events.

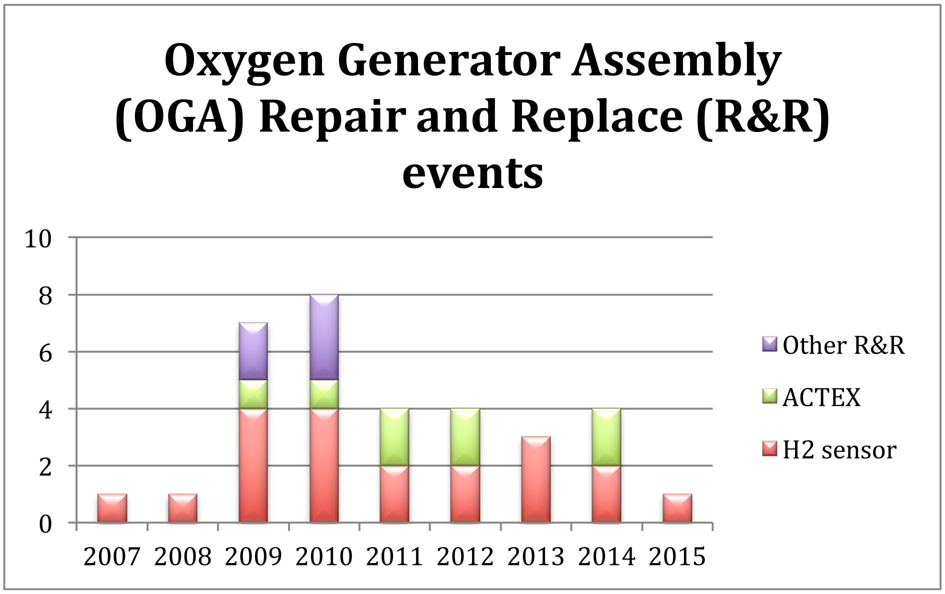

Figure 5. The number of OGA Repair and Replace (R&R) events each year for the H2 sensors, the ACTEX, and other R&R.

The H2 Sensor and ACTEX replacements occur at roughly constant rates of about two each per year. The average total R&R rate in later years is about four per year. The five R&R events other than H2 Sensor and ACTEX replacements are the H2O ORU, Pump ORU, H2 ORU, and two FSE ORU replacements. These are all associated with the Cell stack failure events in 2009 and 2010.

2. The OGA maintenance events from Bagdigian et al.

Bagdigian et al.'s figure 11 shows all the OGA maintenance events and sums up the crew time used. There are 41 R&Rs, 8 more than shown in their earlier figure 10. These form a cluster associated with the Cell stack failure events in mid 2010.

In addition to the 41 R&Rs, there are 36 other maintenance events, for a total of 77. There are ten incidents of cleaning the AAA, not really an OGA event,, four cases of taking recirculating loop water samples classified as inspection, two incidents of removing and reinstalling modified jumpers, four repairs including the H2O ORU filter and recirculating loop flush, and sixteen cases of troubleshooting, which were about half taking water samples with the rest associated with the ACTEX, Pump ORU, and Water ORU. The total of 77 maintenance events are about 80% more than the 43 major events that were identified by Takada et al.

Figure 6 plots the number of OGA maintenance events each year for the H2 sensors R&R, 20 events, ACTEX R&R, 8 events, other repair and replacements, 19 events, cleaning, 10 events, troubleshooting 16 events, and H2O sampling, 4 events.

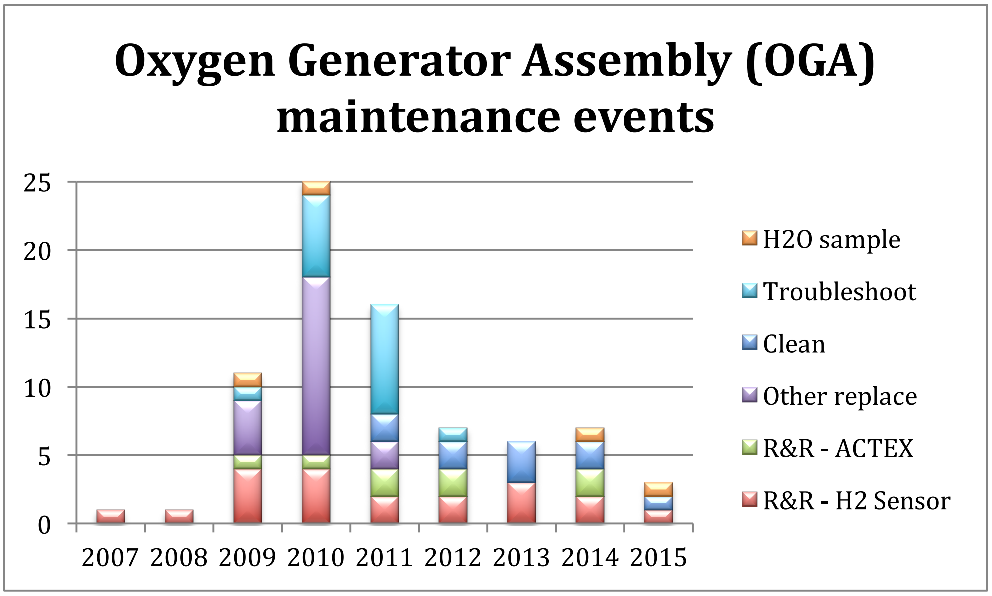

Figure 6. The number of OGA maintenance events each year.

The other replacement events occurred in 2009 and 2010 and were associated with the Cell stack failure. The troubleshooting occurred from 2009 to 2012. The event data shows a major problem being discovered, analyzed, and solved, followed by routine maintenance. All but one event in 2012 or later years is either H2 sensor replacement, ACTEX replacement, cleaning, or water sampling.

C. The ISS OGA would not save mass or cost on a Mars transit mission

The benefit of recycling is often measured by the breakeven date, which is the time required for the mass of the recycling system to be paid for by the mass of materials saved by recycling. This preliminary comparison is not a comparison of oxygen storage and recycling, since the mass of the oxygen tanks is not included. Bagdigian et al.'s figure 10 is a mass breakeven chart that shows the total launch mass actually used to support the OGA and the mass of the oxygen produced over time. It shows the sequence of the 33 ORU Remove and Replace (R&R) events that add to the total OGA mass utilized.

The ISS is a very long duration mission, possibly extending 20 or more years. The ISS OGA can easily pay back its launch mass with the mass of oxygen it provides. Mars missions are much shorter, less than three years total. Typical conjunction class Mars missions have outbound and return transit times of 200 to 250 days each and Mars surface stays of 400 to 550 days. (Boden and Hoffman, 2000) The total transit time that the OGA operates is 400 to 500 days, interrupted by a quiescent period of 400 to 550 days if all the crew is on the surface. An improved ISS OGA could be a candidate for Mars transit but less applicable for Mars surface, where gravity and surface resources are complicating factors.

1. Mass utilized pay back for the ISS OGA on ISS and in transit to Mars

Bagdigian et al.'s figure 10 has a time axis extending from July 2007 to March 2015, 7.75 years. During that time 2,077 pounds of OGA hardware has been utilized and 8,369 pounds of oxygen produced, so the mass of the oxygen is 4.03 times the mass of the OGA hardware used. The time required for oxygen production mass to pay back the OGA launch mass was 7.75/4.03 = 1.92 years, 702 days. Since Mars round trip transits are shorter than 702 days, this ISS OGA performance would not save mass on a Mars mission.

The ISS OGA produced oxygen at a higher rate after July 2011. About 6,400 pounds of oxygen was produced from July 2011 to March 2015, 3.75 years. This mass of the oxygen is 3.08 times the mass of the OGA hardware used. In this later interval, the time required for oxygen production mass to pay back OGA launch mass would be 3.75/3.08 = 1.22 years, 444 days. This launch mass breakeven date is roughly equal to the 450 day average Mars round trip transit time. Even this better ISS OGA performance would not save mass on a Mars transit.

2. OGA system and spares mass pay back on ISS and in transit to Mars

The mass counted in Bagdigian et al.'s figure 10 is the launch mass actually utilized to keep the OGA operating. It does not include the mass of the spares that are launched to ISS and kept on hand to ensure high reliability. Most of the spares now on ISS will never be used, since they required only to insure against failures with low probability.

Suppose an ORU has a low 2% chance of failure over the mission duration, but higher reliability is needed. A spare must be provided, but the chance of actually using the spare is only 2%. The spare mass is mostly not utilized, but a complete account of the mass required to support the system would include all the required onboard spares.

The OGA ORU spares on board ISS and that might be taken on a transit to Mars are shown in Table 5.

Table 5. OGA ORU spares on ISS and for Mars transit.

#	ORU designation	Full name	Onboard spares for ISS	Onboard spares for Mars transit
1	Hydrogen ORU	Hydrogen Pressure dome	1	3
2	Controller	Process Controller	2	3
3	O2 ORU	Oxygen Outlet	1	3
4	H2 Sensor ORU	Hydrogen Sensor	2	3
5	Pump ORU	Pump	2	3
6	Inlet DI Bed ORU	Inlet DI Bed	1	3
7	Nitrogen Purge ORU	Nitrogen Purge	1	3
8	PSM	Power Supply Module	2	3
9	ACTEX	Loop ACTEX	0	3
10	Water ORU	Water	1	3

The number of onboard spares for ISS was taken from the ISS Vehicle Office's Maintenance Data Collection (ISS MDC, 09/04/15). Bagdigian et al.'s figure 10 gives mass of the OGA and the aggregated ORUs. The OGS system mass is 1,487 lb, and the process ORUs, tank ORU's, and controller ORUs are 59% of that total, 877 lbs. Assuming that the ISS OGA has one spare of each of the ORUs, instead of the exact number of spares in Table 5, the total mass of the original system, the additional ORUs utilized, and the onboard spares would be 2,964 lbs. For the actual ISS oxygen production rate of 5.15 lb/day, the time required for the oxygen production to pay back the OGA, used ORU, and spares mass would be 2,964 lbs/5.15 lb/day = 576 days.

Since much higher reliability is required for Mars transit, three spares of each ORU are usually allocated for Mars. (Connolly, 2000) The total mass of the original system plus three sets of onboard spare ORUs would be 4,119 lbs. For the oxygen production rate of 5.15 lb/day, the time required for the oxygen production to pay back OGA and triple spares mass would be 4,118 lb/5.15 lb/day = 800 days.

3. OGA system and spares mass pay back for higher oxygen production in transit to Mars

Bagdigian et al. note that the ISS OGA oxygen production of 5.15.lb/day supports only about 2.9 crew. Takada et al. note that the Mars crew would probably be 4, and that the ISS OGA was designed to produce up to 20.4 lb of oxygen per day for 6 crew plus animals. If 5.15 lb /day of oxygen supports 2.9 crew, 4 crew would require 7.1 lb/day. For this oxygen production rate of 7.1 lb/day, the time required for the oxygen production to pay back the OGA and triple spares mass would be 4,118/7.1 = 580 days, longer than the longest there and back Mars transit time. The breakeven date of 580 days seems realistic. It assumes that the initial system is used with three sets of spares to support 4 crew. It is longer than the longest expected total transit time to Mars and back, 500 days.

4. Supplying the oxygen would be cheaper than using the OGA for ISS, and much cheaper for Mars transit

Bagdigian et al.'s figure 10 and the breakeven date computations based on the data in that figure show that the ISS OGA would weigh less than the oxygen produced on shorter missions such as the Mars transit. Other investigations have shown that oxygen generation does not always save launch mass or Equivalent System Mass (ESM) for similar missions. (Do, et al., 2015-289) (Lange and Anderson, 2012-3491)

If oxygen generation does not save launch mass, it would not save launch cost. However, the launch cost is only one of the costs of providing a recycling system. The Life Cycle Cost (LCC) adds the design, development, and test cost, and the operations cost, to the launch cost. The recycling system design, development, and test cost can be significantly larger than the launch cost. The operations cost can be 10% of the design, development, and test cost for each year of operations.

Oxygen recycling systems are much more expensive to develop and operate per kilogram than oxygen in tanks. The LCC per kilogram of a recycling system can be more than 10 times greater than the LCC per kilogram of resupplied material and tanks. (Jones, 2015-295) This means that the LCC breakeven date for Mars transit recycling could be ten times longer than the oxygen mass breakeven date, 10 to 20 years rather than 1 or 2 years.

On ISS, over 7.75, the 2,077 pounds of OGA hardware that has been utilized has produced 8,369 pounds of oxygen, so the mass of the oxygen is 4.03 times the mass of the OGA hardware used. But if each pound of OGA hardware cost as much to provide as 10 pounds of supplied oxygen, the recycling cost to direct supply cost ratio would be 2,077*10/8,369 = 2.4. Recycling oxygen has cost roughly twice as much as directly supplying it would have been. ISS oxygen recycling is necessary since launching all the crew's oxygen is not now possible, but recycling ISS oxygen does not appear to have saved cost compared to directly supplying it. The ISS OGA could have produced more oxygen if needed would then have had a greater payback.

D. OGA operating lifetimes, reliability, and spares requirement

Bagdigian et al. investigate the OGS ORU reliability by comparing the expected or achieved hardware operating life to a target 1000-day mission length. The OGA ORU predicted and achieved operating lives are shown in their figures 12 through 15. The predicted life is based on calculated Mean Time Before Failure (MTBF), design life, calibration life, estimated limited life, or planned preventive maintenance. All of the OGS ORUs have achieved operating lives on the ISS that meet the 1000-day mission target life with the exception of the H2 Sensor ORU. A demonstrated operating life longer than the Mars transit duration does not mean that a single OGA with no spare ORUs would be a reasonable design. The ISS now carries one or two spares of each OGA ORU. How many of spares each ORU would be needed for Mars? That can be estimated from the ORU MTBFs.

1. OGA ORU predicted and operating lifetimes

Table 6 gives the predicted and observed operating lifetimes from Bagdigian et al. The predicted life and the basis of prediction are given. The number (#) of units operated on the ISS is given along with their proven operating lifetimes. The last column is an estimated MTBF, based on the predicted and observed life times.

Table 6. OGA ORU predicted and proven lifetimes and estimated MTBFs.

#	ORU designation	Full name	Basis for life prediction	Predicted life, hours	#	Proven life	Estimated MTBF
1	Hydrogen ORU	Hydrogen Pressure dome	MTBF	29,500	2	26,000, >44,000	35,000
2	Controller	Process Controller	MTBF	> 70,000	1	>70,000	70,000
3	O2 ORU	Oxygen Outlet	Design life	87,600	1	>70,000	70,000
4	H2 Sensor ORU	Hydrogen Sensor	Calibration life	3,600 (150 days)	18	4 < 500, 14 = 3,600	2,600
5	Pump ORU	Pump	Limited life	17,500	2	25,000, >45,000	35,000
6	Inlet DI Bed ORU	Inlet DI Bed	Preventative maintenance	43,800 (5 years)	1	>70,000	70,000
7	Nitrogen Purge ORU	Nitrogen Purge	Design life	87,600	1	>70,000	70,000
8	PSM	Power Supply Module					
9	ACTEX	ACTEX - Recirculation	Preventative maintenance	13,140 (1.5 years)	3	5,500, 16,000, 12,000	11,000
10	ACTEX	ACTEX –By-Pass	Preventative maintenance	13,140 (1.5 years)	3	21,000, 16,000, 25,000	20,000
11	Water ORU	Water	MTBF	37,800	2	23,000, 52,000	38,000

The predicted and most of the proven life data are from Bagdigian et al.'s figures 12 through 15. These figures have a time span of about 27,000 hours, about three years, and many ORUs have operated longer. Figure 10 shows when ORUs were replaced and allows the current operating lives to be estimated. The hydrogen ORU was replaced in mid-2010, the water ORU in mid-2009, and the pump ORU in early 2010. The controller, oxygen outlet ORU, inlet DI bed, and nitrogen purge have operated for eight years without replacement.

In cases where all the ISS OGA ORUs have reached the end of life, the estimated MTBF is the average lifetime. In cases where one unit has operated without failure for eight years, the MTBF is estimated as eight years, 70,000 hours. If equipment has operated for a time T with no failures, this suggests that the probability of failure was less than one-half. So the MTBF can be estimated as roughly T. If the MTBF was much less, we would have seen many failures. It could be much longer, but longer testing would be needed to show that. We should not optimistically assume the MTBF is much longer than the successful test time. In cases where one unit has failed but its replacement continues to operate, the MTBF is estimated as the average of the two observed lifetimes. Since the two units that failed and were replaced, the Hydrogen and Pump ORUs, both failed due to the membrane degradation problem since fixed by the ACTEX redesign, it can be argued that they should have higher MTBFs. Since this is not demonstrated, we use the actual data.

2. *Using MTBFs for reliability calculations*

The MTBF has a useful direct meaning. Half the ORUs are expected to fail by the MTBF. If the MTBF is equal to the mission length and we have only one system with no spare, the probability of failure during the mission is 50%. If we have a system and a spare, the probability both fail is 0.5 * 0.5 = 0.25, 25 %. To get an overall probability of failure of 1%, 0.01, we need $0.5^N = 0.01$, and N = 6 or 7 units.

If equipment has a certain MTBF, its failure rate is f = 1/MTBF. We need the MTBF to be much, much greater than the mission length, L, to have a single unit provide a low probability of failure. For F = f * L = L/MTBF = 0.01, the MTBF = 100 L. The MTBF must be 100 times the mission length for a single unit without spares to have a 1% probability of failure. If MTBF = 10 L, F = 0.1 and we need two redundant units to achieve $F^2 = 0.01$. If MTBF = 5 L, F = 0.2 and we need three redundant units for $F^3 = 0.008$. This means that, to prove a very low probability of failure for a single unit over the mission length, it would have to be operated without failure for many times the mission length.

3. *OGA ORU estimated MTBFs, failure rates, and spares*

Table 7 gives the OGA ORU estimated MTBFs, failure rates, and estimated spares

Table 7. OGA ORU estimated MTBFs, failure rates, and estimated spares.

#	ORU designation	Full name	Estimated MTBF	ORU failure probability	ISS spares	ISS failure probability	Needed redundancy	Redundant failure probability
1	Hydrogen ORU	Hydrogen Pressure dome	35,000	0.31	1	0.095	5	0.0028
2	Controller	Process Controller	70,000	0.15	2	0.004	4	0.0006
3	O2 ORU	Oxygen Outlet	70,000	0.15	1	0.024	4	0.0006
4	Pump ORU	Pump	35,000	0.31	2	0.029	5	0.0028
5	Inlet DI Bed ORU	Inlet DI Bed	70,000	0.15	1	0.024	4	0.0006
6	Nitrogen Purge ORU	Nitrogen Purge	70,000	0.15	1	0.024	4	0.0006
7	PSM	Power Supply Module			2			
8	~~ACTEX~~	~~ACTEX - Recirculation~~	~~11,000~~	-	~~0~~			
~~9~~	~~ACTEX~~	~~ACTEX - By-Pass~~	~~20,000~~	-	~~0~~			
10	Water ORU	Water	38,000	0.28	1	0.081	5	0.0019
			Totals	1.52		0.280		0.0097

The probability that an ORU will fail over a mission length L is L/MTBF. For the Mars transit, out and back, the mission length L = 450 days, 10,800 hours. The mission failure probability for each ORU is 10,800/MTBF. The failure probability for each ORU is listed. The H2 Sensor is not included, as it is an identified scheduled replacement ORU and may be replaced in a future design. The ACTEX is also a scheduled replacement unit and is not included in the reliability calculations.

The ORU failure probability is summarized for a single string OGA, but the total of 1.52 exceeds a probability of one and is meaningless. [The failure probabilities for ORUs that all must work together can be added, but only if the failure probabilities are small. For high failure rates, the reliability of the ORUs must be multiplied. Suppose the failure probabilities of two series units are each 0.6. The reliabilities are 1 - 0.6 = 0.4, the series reliability that both work is 0.4*0.4 = 0.16, and the failure probability is 0.84, not 0.6 + 0.6 = 1.2.]

All the ORUs except the ACTEX have spares on ISS. The number of ISS spares is shown. One spare gives dual redundancy, two spares give triple redundancy. The probability of not having a needed spare on board ISS would be 0.28, 28%, if it was not possible to replace spares that were used.

We need much higher reliability for the OGA on a Mars transit. Suppose the required reliability is 0.01, 1%. The chance of not having a needed spare must be less than 1%. We need three or four spares, quadruple or quintuple redundancy of the ORUs for less than 1% probability of not having a needed spare. If all ORUs havd only three spares, the probability of not having one when needed would increase to 2%.

A simpler direct calculation can check the math. Assume that the OGA has seven ORUs of concern, as above, each with MTBF = 70,000 hours. Assume that the OGA is required to have less than a 1% probability of failure over the mission length of 450 days, 10,800 hours. The probability that an ORU with MTBF = 70,000 hours will fail over 10,800 hours is 0.15, or 15%. (10,800/70,000 = 0.15) Suppose each ORU has the number N of redundant units. The overall failure probability is $7 * (0.15)^N = 0.01$. N, the number of redundant units of each ORU, must be 4. This is as expected since the ORUs with MTBF = 70,000 hours required quadruple redundancy.

To be able to use less redundancy, we need a longer MTBF. For a longer MTBF, we need longer successful test times. Simply because the Hydrogen, Pump, and Water ORUs failed once during the mission, their MTBFs are cut in half, their failure probabilities are doubled, and they require an additional spare. For accurate measurement of MTBF, we need to test several units for much longer than the mission, preferably until failure.

4. Assuming that all failures can be repaired using spares is optimistic

The above analysis is standard reliability analysis. It is best case, assuming a good, well-tested design, and that all failures can be repaired using spares. But redundancy can be defeated by design errors, external impacts, manufacturing errors, and other kinds of common cause failures. The ISS OGA has had design problems that required redesign. Design errors cannot be repaired using spares on the way to Mars. Relying on standard reliability analysis and assuming that all failures can be repaired using spares is extremely over optimistic. Simple reliability is useful as a best case analysis, since it can identify reliability problems and the need for spares. But providing the estimated spares does not guarantee success. The ISS OGS has limited testing and a high requirement for spares. The previous discussion of launch mass payback assumed that the OGA would need three spares of each ORU. The analysis here suggests three or four spares are needed, including the large Hydrogen ORU. The high mass of the spares means that the ISS OGA will probably not save mass over direct supply of oxygen on the way to Mars. And if the OGA does not save mass, it certainly will not save cost.

VII. Potential issues in improving the ISS OGA for Mars transit

The review of the papers on the ISS OGA by Takada et al. and Bagdigian et al. has found many potential issues that must be solved in developing the ISS OGA for Mars transit.

A. Table of potential issues

The potential issues are given in Table 8, in the order discussed above.

Table 8 Potential issues in developing the ISS OGA for Mars transit.

#	Issue
1	The ISS OGA has reliability and maintenance issues
2	The ISS OGA has extensive planned redesign
3	The ISS OGA requirements differ from the Mars OGA requirements
4	The ISS OGA ORU maintenance is designed for ISS, not Mars
5	The future ISS OGA will have fewer safety systems
6	NASA project planning and systems engineering is to be done
7	The ISS OGA would not save substantial launch mass
8	The ISS OGA would not save cost
9	The ISS OGA has insufficient demonstrated reliability

B. Discussion of potential issues

Each potential issue is discussed above and commented on here.

1. The ISS OGA has reliability and maintenance issues

The ISS OGA has been operating safely and reliably. The reviewed papers are concerned with reducing the current ISS OGA demand for spares logistics and crew time for preventive maintenance and failure repair. Given the ability to resupply the ISS relatively easily and quickly compared to a Mars mission, an ISS OGA failure would probably not cause a threat to the crew. The concern for Mars transit is whether a system similar to the ISS OGA in design and development can be kept working using the available on-board spares and crew time.

2. *The ISS OGA has extensive planned redesign*

Many improvements have been planned for the ISS OGA, including replacing the cell stack membrane material, deleting the nitrogen purge equipment, replacing the hydrogen sensors, deleting the wastewater interface, replacing the hydrogen dome, adding loop water refresh, and redesigning the cell stack power supply. The system architecture and schematic are significantly different. One motivation is to reduce spares and crew time. Any redesign made to cure design issues is likely to introduce new problems that will only be discovered during further operation. Design errors cannot be corrected with spare parts and crew time.

3. *The ISS OGA requirements differ from the Mars OGA requirements*

The OGA for Mars should have lower mass, better reliability and maintainability, greater safety, radiation hardening, and capability for quiescent operation. In general, a system designed for one application and set of requirements is very unlikely to be optimum for a different application and set of requirements.

4. *The ISS OGA is designed for ISS not Mars*

The ORU maintenance approach developed for ISS is workable but not trouble free even for ISS. The ORU approach seems very unsuitable for deep space, and lower level repair is often suggested. The details of lower level repair have not been worked out and implementing a new maintenance approach in existing hardware seems infeasible.

5. *The future ISS OGA will have fewer safety systems*

It is planned to remove the hydrogen dome, the nitrogen purge, and the wastewater interface that were provided to ensure the safe management of hydrogen and oxygen. The justification seems to be that, if it hasn't failed lately, a an over conservative approach and unnecessary equipment were used to make it safe. But a more conservative, not less conservative approach seems needed for Mars.

6. *NASA project planning and systems engineering remains to be done*

In considering using the ISS OGA for Mars, the usual NASA project planning and systems engineering is noticeably not being done. Where are the requirements definition, alternate concept development, and trade-offs? Where is reliability, risk, hazard, and safety analysis? Instead of life cycle cost, we have hardware mass compared to the mass of oxygen produced. Instead of elementary reliability analysis, we have a demonstration that some ORUs have operated longer than the mission length. These are not the standard NASA systems engineering methods.

7. *The ISS OGA would not save substantial launch mass*

The ISS OGA with triple spares for Mars would have somewhat higher mass that the oxygen it would produce on a Mars transit. This single fact alone suggests that using the ISS OGA for Mars is questionable. A much better oxygen generation system is needed to avoid the low technology, brute force approach of supplying the oxygen in tanks.

8. *The ISS OGA would not save cost*

Using launch mass rather than cost to evaluate recycling is traditional in life support. This favors recycling over direct supply, since recycling saves mass but recycling equipment has much higher development and operating cost per kilogram than material in tanks. Unless recycling has a significant launch mass advantage over direct supply, it would not save cost. This suggests that the ISS OGA may not have saved cost for ISS.

9. *The ISS OGA has insufficient demonstrated reliability*

The testing of the OGA ORUs has been largely done on ISS. The original ORUs have been operating over eight years. Even if all the ORUs had operated without failure, the demonstrated reliability would be so low that triple spares are needed for 1% probability of failure during Mars transit. The high OGA mass and the need for triple spares make the ISS OGA uneconomical for Mars transit. The possibility of undetected or newly introduced design errors and other unanticipated challenges make it risky to rely on on-board spares and crew maintenance to keep the ISS OGA operating on the journey to Mars.

VIII. Overview and possible future work

The review of the two papers on improving the ISS OGA for Mars transit has interesting implications for future work.

A. Rethink the initial assumption that ISS life support can be refined for use in Mars transit

Takada et al. suggested that the "proposed incremental improvements" would allow the ISS OGA to be used on a future deep space long duration mission. However, their suggested changes amount to an extensive redesign rather than incremental improvements. Bagdigian et al. ask if the ISS OGA can support a Mars mission. The ISS mass savings and operating lifetimes that they present show that a system similar to the ISS OGA would not save significant mass on a Mars transit mission.

The optimistic assumption that the ISS life support can be improved and used for deep space and Mars is widely shared. “Oxygen generation systems and water recycling systems on the International Space Station today will continue to be refined for deep space travel.” (Bolden, September 17, 2015) Unfortunately, the data provided by Takada et al. and Bagdigian et al. in the reviewed papers do not support the idea that ISS life support is nearly suitable for Mars. Developing life support for Mars will require a more extensive effort.

The OGS pays for its launch mass much more slowly than other life support systems. The water recycling system especially pays for itself in launch mass much more quickly. It is a much better recycling technology to use in Mars transit. A further investigation examines the mass payback of the other ISS life support systems and finds that their material mass payback is higher, but is typically only a factor of two. (Jones, 2016-109)

B. Conduct unrestricted, exploratory, open-ended research into Mars life support

Much past life support research and analysis has been preprogrammed and over controlled. It has been common to define the assumptions, specify the data and methods, and dictate the conclusions.

The original plan for the work reported here had a predefined assumption, goal, method, and expected results. These were:

1. ISS life support can be improved so as to be useable for Mars transit.
2. The goal of improving ISS life support is to reduce the spare parts and crew time needed for maintenance and repairs.
3. The method is to gather ISS data on failure and maintenance events to identify the troublesome parts.
4. The result would be that investments would be recommended to improve the operating life and reliability of the identified parts.

The work of Bagdigian et al. and others followed this same plan, which can be criticized. One problem is that the assumption, goal, method, and expected results all were mistaken, at least for the ISS OGA:

1. ISS OGA would not be not usable for Mars transit. It doesn’t save significant mass. It has different requirements.
2. Spares logistics and crew time are important, especially for ISS in its operational phase, but they are only two resources that must factor in the overall system design trade-offs needed to meet Mars requirements. The optimum design for ISS is not the optimum for Mars.
3. The ISS OGA is well understood by the OGA engineers, who have identified its problems and recommended solutions. The problems extend well beyond troublesome parts and require redesign.
4. In well designed, well tested, long operational systems, failures are random and infrequent and the rates are well known, so the system can be kept operational using a stock of spares sized using the known failure rates. But new unique systems also have failures due to design errors, defective components, unexpected environmental impacts, and operational errors. These can repeat and cascade and so are usually called common cause failures. Common cause failures by definition are any that would defeat the use of redundant parts. Design changes are often needed and would be very difficult during a mission. The ISS OGA has had and still has failures and problems requiring redesign.

Predefining the methods and conclusions is not a good research method. It would be better to follow a more scientific approach, which tests rather than accepts assumptions, and which encourages open debate rather than conformity to consensus conclusions.

C. Next steps

There are useful next steps in planning life support for Mars. These include:

1. Do a top-down, end-to-end look at life support requirements for Mars. Without predefined requirements, it was difficult to evaluate the ISS OGA for Mars transit. The requirements should focus on mission level performance including costs, safety, and operability. They should in no way constrain implementation.
2. Consider the reliability, maintainability, and redundancy approach for Mars life support. It is generally understood that the ISS maintenance approach using ORUs is unsatisfactory. Each large ORU repairs only a single failure. It is thought that lower level maintenance would be better, but the best approach for Mars is not clearly understood.
3. Use the NASA project phasing and systems engineering approach. First define the requirements and then do the systems engineering trade-offs to identify the best system to meet requirements at the minimum cost, including dollars, launch mass, and crew time. Candidate solutions should be tested against the requirements and each other.

Conclusion

Using the ISS oxygen generation system is not a feasible approach for Mars transit. It would produce less than its own weight in oxygen, so it would not save much launch mass. Saving launch mass is a much more achievable goal than saving cost, so the ISS oxygen generation system would probably cost more than oxygen in tanks if used for Mars transit.

The ISS oxygen generation system requires a significant redesign for satisfactory operation on the space station. The planned extensive improvements would be insufficient for Mars because Mars life support has significantly different requirements than ISS. These include lower mass, better reliability and maintainability, greater safety, radiation hardening, and capability for quiescent operation.

The standard NASA systems engineering process was not used to evaluate employing the space station oxygen generation system for Mars transit. It was assumed that using the space station oxygen generation system was sufficient.

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