

Evaluating the Applicability of Heritage Flight Hardware in Orion Environmental Control and Life Support Systems

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Recent changes in the overall NASA vision has resulted in further cost and schedule challenges for the Orion program. As a result, additional scrutiny has been focused on the use of new developments for hardware in the environmental control and life support systems. This paper will examine the Orion architecture as it is envisioned to support missions to the International Space Station and future exploration missions and determine what if any functions can be satisfied through the use of existing, heritage hardware designs. An initial evaluation of each component is included and where a heritage component was deemed likely further details are examined. Key technical parameters, mass, volume and vibration loads are a few of the specific items that are evaluated. Where heritage hardware has been identified that may be substituted in the Orion architecture a discussion of key requirement changes that may need to be made as well as recommendation to further evaluate applicability are noted.

Nomenclature

I. Introduction

Recent changes in the overall political environment of the country has led to increasingly tight budgets throughout all government agencies and The National Aeronautics and Space Administration (NASA) has not been immune. With increasing emphasis being placed on cost and schedule of the Orion Crew Exploration Program, efforts have been renewed to evaluate the use of new developments for hardware in the environmental control and life support systems (ECLS). The ECLS system is comprised of the air revitalization subsystem, the pressure control subsystem, the potable water subsystem, the fire detection and suppression subsystem and the active thermal control subsystem. With this breadth of functionality, it is not surprising that the ECLS is a significant portion of the cost for the overall program. Additionally, with the amount of complex hardware that comprises the ECLS, schedules for delivery of this hardware are often time in or near the critical path for the vehicle build.

Previous studies have looked at the complexity (add reference to 2008 Apollo comparison paper) of the Orion ECLS and compared it to similar functionality used for the Apollo program. That paper concluded that sufficient evolution of requirements, heat loads and technology has occurred that the increase in mass and volume from Apollo to Orion is warranted. This paper will take a different approach to the historical assessment and will focus on the

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potential use of heritage Shuttle, International Space Station or even X-38 ECLS hardware. After a brief summary of the current Orion architecture to set the context of the discussion, we will examine a top level look at all of the components and their potential for use on Orion. We will conclude the paper by doing a more involved analysis of three specific components, the positive pressure relief valve, the radiators and water tanks.

II. System Overview

While the current focus on the Orion program is on flight test 1 (OFT1) with ECLS functionality limited to only active thermal control components needed to support a similarly limited avionics and power suite, this assessment was done based on the ECLS functionality represented by the hardware configuration designated 606H. This configuration is designed to support a mission to the ISS or to the moon with functionality to include launch and return of up to 4 crew members. Further information on the details of this configuration can be found in [include reference to 2009? ECLS overview paper]. A schematic of this configuration is included in Figure #<check for LM approval for schematic dissemination>.

III. Heritage Hardware Assessment

The heritage hardware assessment followed a logical process by which the everyone of the baseline components were evaluated for technical applicability as well as cost. First, we assessed the function represented by the component and asked the question “Could a heritage piece of Shuttle or ISS hardware be used to perform this function?” If the answer was “yes”, the specific heritage hardware was identified, as were any open issues relative to its use. If the answer was “no”, then an explanation of why not was noted. Second, we evaluated each function for whether it should be considered something that NASA should provide as government furnished equipment (GFE). This assessment considered the availability and suitability of the heritage hardware, the existing functional expertise and whether that expertise was resident within NASA, the desire of NASA to procure directly from vendors to preclude additional contractor overhead costs, and whether this function is already being provided for earlier missions. An example of the spreadsheet that was generated to collect all this data is included in Figure #.

Once complete this assessment evaluated 132 components or groups of components (e.g., tubing was considered a group of components). These components could then be organized into five groups, the breakdown of these groups is shown in Figure #. The first category included 10 components where heritage hardware may exist and has the potential to be considered new NASA GFE. The second category includes the components where heritage hardware does not exist, but NASA has the expertise to develop it in-house as new GFE. Approximately 20 components fell into this second group. The third group of components contains the largest number of parts at 40 and this group is of hardware where no heritage hardware is available but NASA could potentially save the overhead costs of using a sub contractor by directly purchasing these parts directly from a vendor. The fourth group of components is the 30 components that are required to support the Orion Flight Test 1 (OFT1) project and are therefore already in the design and development cycle. At this point it would impact the test schedule to change direction and attempt to use heritage hardware or build this hardware as GFE. The last group of 32 components were deemed to integral to the vehicle design or assembly to consider heritage hardware or GFE as an alternative. This group contains such items as tubing, ductwork and vents. The latter two categories will not be discussed further as no additional work was identified.

Further examination of the 10 components that were identified as having potential heritage hardware substitutes were further evaluated. These components included the positive pressure relief valve (PPRV), and the ground support heat exchanger (GSE HX). For OFT1, we have already evaluated the ISS programs multipurpose logistics module positive pressure relief assembly (PPRA) and determined that for the unique requirements of that flight, the PPRA will provide sufficient functionality and was designed to adequate environments to cover the OFT1 flight profile. We have recently received agreement from the ISS program to transfer two PPRA’s from their inventories to the Orion project late summer 2011. Similarly, the Shuttle Freon to Freon ground support heat exchanger was evaluated for use on the OFT1 vehicle and has been deemed acceptable for use. Transfer of one of the Shuttle spare GSE HX’s is in process to support the July 2013 flight of OFT1.

The remaining hardware in that category includes a cold plate bypass assembly which is a simple open/close valve that the prime contractor has yet to start procurement on and it is believed that any number of valves in the Shuttle and ISS fleet may support this function. The snorkel fan outlet valve and smoke detector have similar functionality to the ISS inter-module ventilation valve and the ISS smoke detectors. The cabin and hatch pressure equalization valves may also have ISS and shuttle valves that can be re-engineered with little effort to support Orion requirements. Finally, the potable water tanks may be of the right size that existing potable water tanks can be used. The team recommendation for this group of hardware is to pursue each of them further to determine if heritage

hardware does exist and can it be used for Orion purposes. However, there are reservations associated with the significantly higher vibro-acoustic loads that are being levied on Orion hardware, the availability of the parts for the electronic hardware, unique requirements from the exploration standpoint (e.g, radiation hardening), and the need to restart hardware production lines at vendors that may not longer be producing heritage hardware.

The 20 components where no heritage hardware was identified but NASA has the expertise to develop them as new GFE include items that NASA was already providing as GFE and several new candidates. NASA was already providing the portable fire extinguisher, emergency masks, contingency gas analyzer, ammonia/hydrazine sensor for post landing and potable water bags. With the recent focus on the OFT1 mission and subsequent delay in the design and development of a significant portion of the ECLS system, there are additional components that are candidates to be provided as GFE. These include such things as the entire suit loop. This would include providing the carbon dioxide removal systems, regulators, fans, air monitoring, trace contaminant control and the liquid cooling garment water loop. In addition to the suit loop, the government could also provide LiOH for post landing, the potable water dispenser and the potty. The latter would mostly scavenge the extended duration orbiter system or possible an upgrade based on exploration technology development programs. In this area, we will be pursuing a detailed proposal for these items in order to determine what if any advantages may be evident in this path in terms of cost, schedule and technical resources. The proposal will be completed during fiscal year 2012.

For the largest category of components where no heritage hardware was available it was often noted that the components themselves were already either a derivation from or using similar development tools as much of the heritage hardware. In this area hardware changes are driven mainly by the unique requirements of the Orion projects and in most cases due to the vibro-acoustic loads. For example, the sublimator used for lunar missions is a direct descendant of the sublimator used for the Apollo lunar module and subsequently for the X-38. Where it has been modified it is due to the aforementioned loads or limitations on mass and volume. Generally, the hardware in this category is best left to the prime contractor and their partners. However, it was noted that we need to continue working with the contractor groups to reduce costs wherever possible.

In parallel to this assessment, 3 components were chosen to do a more in depth technical assessment. These components are discussed in the following sections.

IV. Positive Pressure Relief Valve

The X-38 utilized a PPRV that was an off-the-shelf, heritage spacecraft component supplied by Carlton (now Cobham). It was almost identical with the Space Shuttle Orbiter and MPLM PPRV's; minor differences are noted in Table # below. Conceptually, it can be described as a mechanical relief valve combined with an upstream, motor-driven butterfly valve. The assembly includes a manual override to the motor driven section, micro-switch position sensors on the butterfly valve, and a visible position indicator on the manual override handle.

The Orion PPRV is currently planned to be a customized design driven by unique Orion requirements, although based on the heritage Shuttle / MPLM configuration. The major differences between the X-38 and Orion PPRV's are the mass flow rates (Orion valve 5.3 times greater), leakage rates (Orion valve 1/4 as much), maximum design loads (Orion valve up to 60 percent greater), and factors of safety on design loads (Orion valve 43 percent greater for nominal loads).

Mass Flow Rate The Space Shuttle / MPLM PPRV, also used on the X-38, has a full open mass flow rate of 150 lbs air / hour, at a maximum pressure drop of 16.0 psid. This value was determined by the Shuttle's 14.7 psi cabin nitrogen pressure regulator, which has a full open flow rate of 125-150 lbs/hour.

The much greater mass flow rate of the Orion PPRV, 800 lbs air/hour, is driven by the fixed fire suppression system for the avionics bays, which utilizes nitrogen gas as the fire suppressant. Current Orion fire suppression requirements:

- a. Prohibit the use of halon, due to its very negative effects within the ISS life support system, even in very small trace amounts;
- b. Specify that fire suppression within the avionics bays be operable during lunar quiescence (when the vehicle is at least partially active, but uncrewed);
- c. Specify that fire suppression within the avionics bays be operable during ascent and entry (when the crew would be confined to their seats, and unable to connect a portable fire bottle to a fire port).

In addition, the following derived requirements for the Orion fire suppression system are based on general guidance from the safety and fire science communities:

d. Once the system is activated, the oxygen concentration within the avionics bays should be reduced to less than 10.5 percent within 2 minutes;

e. The oxygen concentration within the avionics bays should be held at less than 10.5 percent for 20 minutes;

After much discussion early in the design process, nitrogen was selected as the suppressant rather than carbon dioxide, because the introduction of large quantities of carbon dioxide into the confined cabin volume would have negative consequences for crew respiration.

It is also relevant that the avionics bays cannot be hermetically sealed off from the cabin, because

- a. They must be able to vent internal pressure in the event of a cabin depressurization or fire event; and
- b. When the fire suppression system is activated, the effectiveness of the system will be much greater if the oxygen present is able to flow out of the avionics bays, as it is displaced by another gas.

Although subject to future refinement, current estimates are that 7.9 pounds of nitrogen, introduced to the avionics bays within 2 minutes, is required in order for the Orion fixed fire suppression system to meet all requirements (including allocations for leakage, tank fill inaccuracy, etc). The rapid introduction of this much additional nitrogen into the cabin, especially during the initial few seconds when the tank pressures and mass flow rates are very high, constitutes a mass flow rate of up to 800 lbs / hour during the first portion of the discharge period. This is many times greater than the full flow rate of a failed open pressure regulator, the largest of which is the high-rate contingency oxygen regulator located in the MPR01 CEI, with a full open flow rate of approximately 55 lbs/hour of oxygen. Thus, the rates of mass introduction into the cabin from the fixed fire suppression system, and the associated cabin pressure increase, are what sizes the mass flow rate of the Orion PPRV. The full flow rate of the Shuttle / MPLM / X-38 PPRV constitutes only 19 percent of the Orion requirement.

Leakage In order to meet allocated leakage requirements, the Orion PPRV needs to leak no more than 8.2×10^{-5} scc/second of air (0.00492 scc/minute). The Shuttle / MPLM / X-38 leak rate is 3.24×10^{-4} sccs of air (0.01944 scc/minute), approximately four times greater. In other words, the Shuttle / MPLM / X-38 PPRV leaks four times more air than the Orion specification, and technically would not meet Orion requirements. However, the difference in terms of the mass of air leaked is negligible. Over a 210-day mission duration, the difference between the two leak rates is only an additional 0.012 lbs of air.

Maximum Design Loads and Factors of Safety The Statement of Work for the X-38 PPRV specified the maximum static loads as 40g along any one axis, and 10 g on the two remaining (presumably orthogonal) axes.

A factor of safety on the X-38 loads was not specified explicitly in the X-38 Statement of Work. However, a dynamic loading environment equivalent to 140% of the static loading was specified. In the opinion of NASA/Wayne Jermstad (email, 9/24/10), this is equivalent to a factor of safety of 1.4 on the static loads. Per the December 2009 Environmental Definitions Document, Orion static load requirements are 11.7g for nominal launch loads, and 64.2g for off-nominal launch loads. These are the same for all three axes. Finally, Orion ECLSS has a factor of safety of 2.0 on nominal static structural loads, and 1.4 for off-nominal loads.

The Orion static load requirements and factors of safety are greater due to the more severe accelerations that the spacecraft may experience, especially when failure scenarios are considered that should be survivable, such as launch aborts and failed-parachute landings.

It is unclear whether the Shuttle / MPLM / X-38 PPRV design could meet Orion load requirements. Load testing of those valves was apparently not performed to the higher Orion levels, and test units were apparently not tested to failure. Therefore, at a minimum, re-testing and re-qualification to the higher Orion loads and factors of safety would be required.

The largest driver for the size and weight of the Orion PPRV, and the primary reason that the X-38 design does not meet Orion requirements, is the necessary flow rate, which is driven by the gas introduced to the cabin by the fixed fire suppression system. The higher Orion structural loads and factors of safety are, most likely, an additional factor in the cost and weight of the component.

Re-use of the Shuttle / MPLM / X-38 PPRV design on Orion would require both of the following: Re-design, or removal, of the Orion fixed fire suppression system and re-testing and re-qualification of the heritage PPRV design to the higher Orion structural loads and factors of safety.

With regard to the fire suppression system, changing from nitrogen to a different inert gas, such as argon, would have little to no effect on the amount of gas required, and the resulting flow needed out of the PPRV.

As mentioned earlier, the presence of Halon is strictly forbidden on all ISS visiting vehicles, with the exception of the Space Shuttle. The problem here is that the high-temperature catalytic atmospheric revitalization processes in use on ISS break Halon down into some very hazardous byproducts, which are toxic at very low levels, and no known containment is sufficient to keep the Halon from leaking out in quantities that are measurable and significant, over long durations. The only reason the Space Shuttle program received an exception was because Space Shuttles aren't docked to ISS for very long, and it would have been too expensive for them to change their existing fire suppression design. All other ISS visiting vehicles must avoid the use of Halon.

Water foam would not work as a fire suppressant within avionics bays in zero-g, for several reasons. The suppressant material must fill and/or coat the entire inner volume of the bay, including many oddly-shaped boxes and restricted flow passages, as well as the interiors of those avionics boxes. This is difficult to achieve with a liquid. There are also issues with clean-up after a release of water foam fire suppressant, and the effects of residue from the foam on electronics and electrical components.

Some recent technology development work has been done on water mist as a fire suppressant, which utilizes very fine droplets of pure water, almost fog-sized, which behave more like a neutral gas for flow purposes. This approach holds some promise, since the addition of a sufficient quantity of water mist to an avionics bay to suppress a fire would not have a large effect on the overall cabin pressure, and would leave no residual contamination. Investigation into this approach is on-going.

Another option would be the deletion of fixed fire suppression from the Orion spacecraft. The original Orion fire control strategy relied on a materials certification approach that would have certified all materials used in the avionics bays to be non-flammable at an oxygen concentration of 40 percent, 10 percent higher than the maximum cabin oxygen concentration of 30 percent. Combined with minimal or no flame propagation within the avionics bays due to a lack of forced air flow there, this was seen as sufficient justification by the program for not requiring fire detection and suppression within the avionics bays. However, this approach was not ultimately pursued, due to the significant time and expense associated with materials certification to the higher oxygen levels. The ultimate problem was a lack of data. Instead of determining what the flammability limits of each material really were, existing (legacy) materials and flammability certifications from the Shuttle and ISS programs had stopped at 30 percent oxygen, so the data required for a timely adoption of the new Orion approach was not available.

In the three-plus years since the proposed fire control strategy was dropped in mid-2007, additional work has been done on materials testing and certification to oxygen concentrations above 30 percent. Given sufficient interest at the program level, it might be possible to revert to the original Orion fire suppression strategy, and delete fixed fire suppression from the design. A very approximate estimate of the associated weight savings for the spacecraft would be on the order of 20 pounds, representing the mass of the nitrogen fire suppressant, tankage and tubing removed, and taking credit for a smaller PPRV.

V. Radiators

A similar comparison was done for the radiator systems used for the ISS and for shuttle. This comparison however is limited to the construction of the hardware. This is primarily due to the significant differences in heat loads required for each of the programs. More specifically, the Shuttle radiators are designed for a maximum heat load of 25kW and the ISS radiators are designed to provide approximately 11.7kW per orbital replacement unit with 6 ORU's nominally in operation providing a total capability of approximately 70kW total. Orion, in perspective, is expected to need no more than 5 to 7kW for the long duration lunar missions. Given this obvious disparity in heat rejection across the various vehicles was evaluated on mass per kW basis in order to provide a good comparison. **Table #** provides a comparison of salient requirements between the three programs.

....complete table and provide synopsis.

VI. Tanks/Accumulators

A comparison of several tanks and accumulators was also completed. This assessment looked at the ISS recycle filter tank assembly (RFTA), the ISS waste water storage tank assembly (WSTA), the X-38 water tank, the Shuttle water spray boiler (WSB). **Table #** includes a top level comparison of these tanks.

....complete table and provide synopsis.

VII. Conclusion

Given the current fiscal challenges of the agency, it is necessary to understand the factors driving the cost of the current Orion systems. In order to better understand the difference between Orion hardware and previous spaceflight environmental systems two different activities were completed. The first activity was a detailed assessment that compares the components necessary for the Orion ECLS system with heritage hardware performing similar functions. This assessment highlighted several areas where additional effort will be put into evaluating whether additional hardware can be provided by NASA as government furnished equipment. Completion of these proposals in FY12 will identify any cost, schedule or technical advantages to having NASA provide this function as GFE. The second activity included looking at the technical specifications of specific hardware to understand what may be driving significant cost or schedule differences for the Orion specific hardware. This activity highlighted that in some all areas, vibro-acoustic loads are significant higher than those levied on ISS or shuttle hardware while in other cases, heritage design is applicable to Orion and should be considered as a cost reduction exercise.

Module	Subsystem	Description of HW	Heritage HW candidate?	If yes, identify heritage HW	If no, explain why not	GFE candidate?	Rationale for GFE decision	Bar
CM	Active Thermal Control - Unpressurized	Radiator Inlet Manifold Subassembly (RIM1)	yes	HS already going to Moog which was used on ISS. Cost is in cert for Orion.		no	1) this is an OFT1 component and transition to NASA GFE would disrupt schedule. 2) Savings of wraps estimate at 25% or \$344K, but NASA would have to pick up procurement, integration, and certification effort at some cost.	1378
CM	Active Thermal Control - Unpressurized	Radiator Outlet Manifold Sub (ROM1)	yes	HS already going to Moog which was used on ISS. Cost is in cert for Orion.		no	1) this is an OFT1 component and transition to NASA GFE would disrupt schedule. 2) Savings of wraps estimate at 25% or \$344K, but NASA would have to pick up procurement, integration, and certification effort at some cost.	1378
CM	Active Thermal Control - Unpressurized	Cold Plate - Battery (CP07, CP08)	no		Based on heritage designs, but very specific to Orion, and with PGW, heritage part numbers won't work	no	already in work for OFT1	855
CM	Active Thermal Control - Unpressurized	Cold Plate - PDU C1/C2 (CP31, CP32)	no		Based on heritage designs, but very specific to Orion, and with PGW, heritage part numbers won't work	no	already in work for OFT1	881
CM	Active Thermal Control - Unpressurized	Cold Plate - PDU (CP29, CP30)	no		Based on heritage designs, but very specific to Orion, and with PGW, heritage part numbers won't work	no	identical to CP31/32	
CM	Active Thermal Control - Unpressurized	Ammonia Boiler Subassembly (ABHX-1, ABHX-2)	no		Shuttle (Fairchild) offline now. Would be challenging to reservice. Obsolescence issues, and too big.	no	OFT-1 time critical. Don't have expertise, would only save CPE cost (12%), with some delta cost for NASA to assume this role. Would still need to be Hamilton component	10070

Figure 1 Example Heritage Hardware Spreadsheet

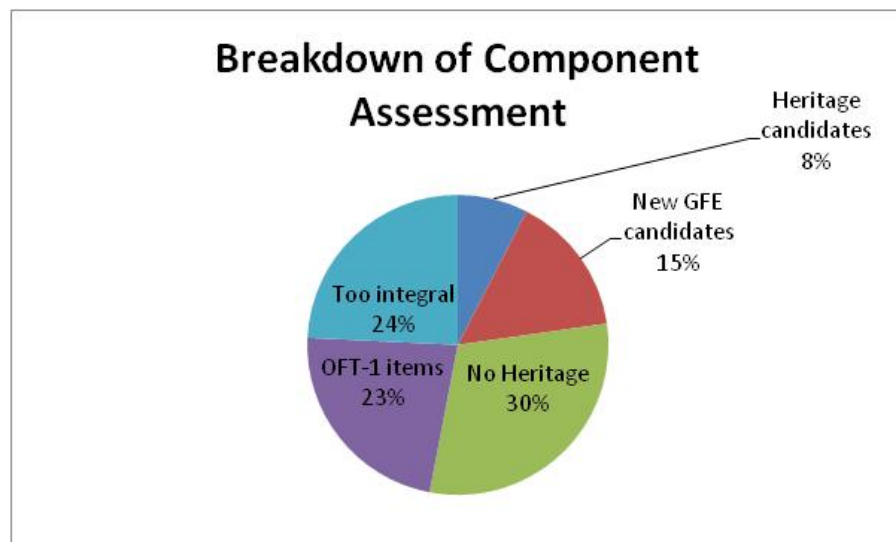


Figure 2 Breakdown of Component Assessment

Table 1 Comparison of PPRV Physical and Performance Characteristics

	Shuttle / MPLM PPRV (minor differences noted)	X-38 PPRV (same as Shuttle/MPLM, except as noted)	Orion PPRV
Weight	3.35 lbs (valve portion only) 5.5 lbs (including	Same as Shuttle / MPLM	8-10 lbs (estimated)

	exterior non-thrust vent and cap assembly)		
Full-Flow Pressure	16.0 psia inlet, 0 psia outlet (MPLM 15.42 psia inlet)	Same as Shuttle	15.55 psia inlet, 0 psia outlet
Minimum Reseat Pressure	MPLM 14.93 psid; Shuttle not specified	15.5 psid	Not specified explicitly, but leakage requirement must be met at or below 15.15 psid
Full Open Mass Flow Rate	150 lbs air / hour minimum	Same as Shuttle	800 lbs air / hour minimum
Power Draw (for butterfly valve motor)	2.8 watts for 2 seconds, 28 v dc	Not specified	Maximum of 10 watt-seconds
Leakage	3 x 10 ⁻⁴ scc/second (0.018 scc/minute) of helium, maximum, = 3.24 x 10 ⁻⁴ sccs of air (0.01944 scc/minute)	Same as Shuttle	8.2 x 10 ⁻⁵ scc/second of air (0.00492 scc/minute)
Design Loads		Static load factor for any single axis: 40g Simultaneous load factors for two remaining orthogonal axes: 10g	Nominal launch: 11.7g Off-Nominal launch: 64.2g (combination of steady-state, quasi-steady state, and random vibration; same for all three axes)
Factor of Safety on Design Loads		1.4	2.0 for nominal, 1.4 for off-nominal

Table 2 Comparison of Program Water Tanks

	ISS RFTA	ISS WSTA	X-38 Water Tank	Shuttle WSB Tank	Orion Water Tank
Weight		100 lbs	61 lbs		57 lbs
Max Design Pres	35 psig	30 psig			
Total Volume			6699 in ³		6377 in ³
Fluid Capacity		832 in ³			

Vibration Loads	9.47 g (rms)	6.3 g(rms)		f 0.14 g ² /Hz from 60 to 150 Hz.	December 2009 EDD + 6 dB is 28.0 g ² /Hz from 50 to 125 Hz
Design Loads					32.1 g