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Co-Storage of Cryogenic Propellants for Lunar Exploration

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Liquid hydrogen and liquid oxygen provide the highest specific impulse of any practical chemical propulsion system. Future manned missions will require vehicles with the flexibility to remain in space for months, necessitating long-term storage of these cryogenic liquids. For decades cryogenic scientific satellites have used dual cryogens with different temperatures to cool instruments. This technology utilizes a higher temperature cryogen to provide a stage that efficiently intercepts a large fraction of the heat that would otherwise be incident on the lower temperature cryogen. This interception reduces the boil-off of the lower temperature cryogen and increases the overall life-time of the mission. The cryogenic propellant *Co-Storage* concept is implemented similarly; the liquid oxygen, typically at ~ 100K, thermally shields the liquid hydrogen, typically at ~ 25 K. A thermal radiation shield that is linked to the liquid oxygen tank shrouds the liquid hydrogen tank, thereby preventing the liquid hydrogen tank from being directly exposed to the 300 K external environment. Modern passive and active technologies such as cryocoolers can eliminate the liquid oxygen boil-off and also cool the thermal radiation shield, thereby reducing the liquid hydrogen boil-off to a small fraction of the unshielded rate. The thermal radiation shield can be a simple conductive shroud or a more sophisticated but lighter Broad Area Cooling (BAC) shroud. This paper compares the spacecraft-level impacts of the BAC active co-storage concept with a passive co-storage option in the context of two of the different scales of spacecraft that will be used for the lunar exploration effort — the Orion and the Ares V Earth Departure Stage.

I. Introduction

Long-term storage of cryogenic propellants enables greater payload capacity for NASA's effort to return to the moon. Liquid hydrogen/liquid oxygen has the highest specific impulse of any practical chemical propellant combination, providing the greatest payload mass per unit of launch mass. The mass of a cryogenic propellant system however, must take into account boil-off up till the time of use. Developments in scientific cryogenic payloads and emerging technologies such as Broad Area Cooling (BAC) can however be used to reduce and in some case eliminate this boil-off. There are four major components for the Lunar Architecture that might reap benefits from long-term cryogenic storage in space: the Orion, the Earth Departure Stage (EDS), the Altair Descent and the Altair Ascent.

Historically, the need for long-term storage of cryogenic propellants such as liquid hydrogen and liquid oxygen has been limited to launch vehicles that have hold times on the order of hours, since the propellant tanks were filled and topped off just prior to launch. The current lunar architecture calls for two independent launches: The Ares I will launch the astronauts in the Orion crew exploration vehicle. Ares V will launch the EDS and the lunar lander Altair Descent and Ascent modules. The EDS and Altair may be parked in LEO to allow for any launch slippage on the Ares I launch. The assumed maximum loiter time has varied from 4 to 95 days in different studies. The greater the maximum loiter time, the more flexibility that there will be for launch operations. Long term storage of cryogenic propellants is crucial for this part of the architecture as both the EDS and the Altair Descent will use liquid hydrogen/liquid oxygen. Once both launches are completed, the Orion will dock with the Altair and the EDS. The EDS will then perform a trans-lunar-injection (TLI) burn to send the Altair and the Orion towards the moon. The Altair descent will perform a lunar capture burn. The Altair will then undock from the Orion and the Altair Descent will subsequently perform a descent burn that will carry the Altair Ascent and the astronauts to the lunar

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surface. The astronauts may stay for 180 days or longer on the lunar surface for outpost missions. During this time the Orion will stay in lunar orbit. At the end of their stay, the astronauts will launch from the lunar surface on the Altair Ascent and then dock with the Orion. The Orion will then return the astronauts to the Earth. Enhancement of payload capacity can be achieved by using liquid hydrogen and liquid oxygen for the Orion and Altair ascent. The long term storage and handling of cryogenic propellants is thus a common goal across all components of the Lunar Architecture, and development of this technology is essential for the success of the lunar program.[1]

Although liquid hydrogen and liquid oxygen have not been stored in orbit for long periods, liquid helium tanks have flown in numerous scientific missions, and have hold times of months to years.[2,3,4] Long term storage of liquid helium in space has been demonstrated successfully despite some major physical disadvantages that smaller liquid helium tanks have relative to large liquid hydrogen or liquid oxygen tanks: The heat of vaporization of hydrogen is more than a factor of 20 times that of helium, and helium tanks for scientific missions are typically much smaller than propellant tanks, and thus have much larger surface area-to-volume ratios. Often, the liquid helium is part of a dual cryogen system. A higher temperature cryogen, such as neon, is used as a thermal buffer where heat can be intercepted more efficiently, thereby limiting the heat on the helium tank and thus reducing the helium boil-off. We term the storage configuration in which two cryogens are stored such that the properties of one cryogen are used to limit the boil-off from the second cryogen as "Co-Storage."

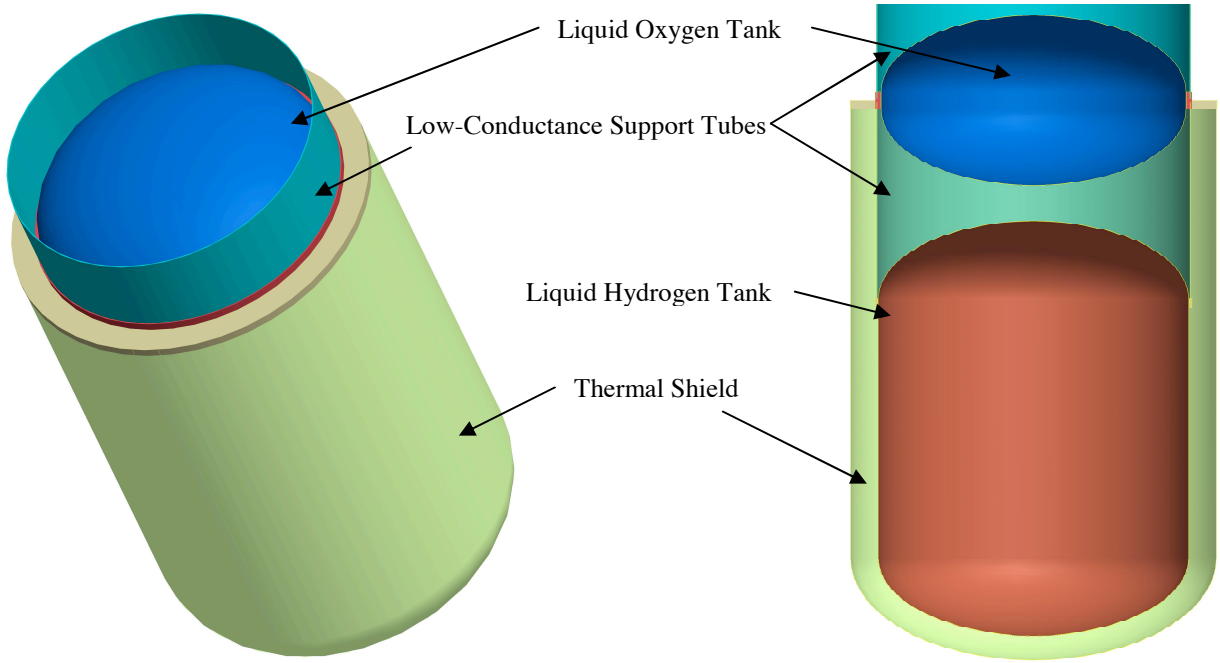
This paper presents the spacecraft level impact of two different types of *co-storage* systems – active and passive systems. Depending on the size of the propellant tanks and the mission duration there is a design point where it becomes more mass-efficient to use the active method. This paper explores this trade in greater detail for two components of the lunar architecture – the Orion and the Ares V EDS.

II. Co-Storage

The concept of co-storage has been used on scientific payloads where dual cryogen systems are used for long-term handling of cryogens in space. Dual cryogen systems typically have of a vacuum-jacket, which effectively eliminates the convective and gas conduction heat load on the system while it is in the atmosphere. Inside this vacuum jacket, low conductance structures support and isolate the higher temperature cryogen from the ambient environment. The lower temperature cryogen is similarly isolated from the higher temperature cryogen with low conductance structures. A thermal radiation shield that is thermally coupled to the higher temperature cryogen tank protects the lower temperature cryogen from directly viewing the ambient environment. Most importantly, many layers of multi-layer insulation (MLI) are used to minimize the radiative heat load into the tanks. A co-storage system for propellant tanks would not have a vacuum-jacketed outer shell since such a self-supporting structure would be prohibitively massive. Instead the tank would be coated with foam insulation - similar to the foam used on launch vehicle tanks – that would reduce the convective and gas conduction heat load while the co-storage system is within the atmosphere. The oxygen tank would be covered by 25 mm thickness of this foam and the hydrogen tank would be covered by 50 mm of foam.[5] The foam layer would also be covered by about 40 layers of MLI that would limit the radiative load on the tanks, once the tanks are in orbit. A cylindrical or conical shell of low thermal conductivity material such as a fiberglass composite would provide support and isolate the oxygen tank from the ambient and would similarly support and isolate the lower temperature (~ 25 K) hydrogen tank from the higher temperature (~ 100 K) oxygen tank. If an active system is used then a thermal radiation shield for the hydrogen tank will be thermally attached to the oxygen tank to limit the radiative load on the hydrogen tank. The oxygen tank and the thermal shield will be cooled using a mechanical cryocooler. If a passive system is used then the effectiveness of the hydrogen tank shielding must be designed to allow sufficient hydrogen boil-off to completely intercept the heat into the oxygen tank and eliminate its boil-off. Figure 1 depicts the co-storage concept for storing cryogenic propellants.

A. Active Co-Storage

An active co-storage system uses a thermal radiation shield that is thermally anchored to the liquid oxygen tank. Figure 1 shows a Co-Storage unit that uses a conductive, self-supporting thermal shield physically supported from the oxygen tank. The tank and shield are conductively cooled to 100 K with mechanical cryocoolers. Depending on the tank size, a small number of existing coolers with space-flight heritage could handle the heat load. A disadvantage of a self-supporting, conductively cooled shield is that its mass scales up rapidly with size. This problem can be circumvented by using a configuration termed broad area cooling (BAC).[6] In a co-storage system, the circulating gas would also cool the oxygen tank, preventing any oxygen boil-off. By keeping the shield near 100K the system reduces the radiative heat flux on the hydrogen tank from about 0.25 W/m^2 to 0.02 W/m^2.



(a) Isometric View **(b) Cross-Section**

Figure 1. A co-storage unit.

Although it is possible to cool to liquid hydrogen temperatures with a mechanical cooler, the Carnot Law demands that the efficiency (watts of cooling per watt of power required) drops linearly with temperature, and in practical flight cryocoolers other losses cause efficiency to drop as T^2. Thus, there is a thermodynamic advantage to absorbing the heat at a higher temperature. Furthermore, numerous single stage coolers, many with flight heritage, can reach temperatures of 100K, whereas multistage coolers that can achieve below 30 K have only been brought to TRL-6.

B. Passive Co-Storage

The passive co-storage concept is an alternate storage technique that can be implemented in a configuration similar to the active co-storage concept. This configuration, proposed by Le Bar and Cady[7], is an open system in that the gas flowing through the network of tubes is the boil-off from the hydrogen tank instead of the circulating helium gas. The shielding of the hydrogen tank must be optimized so that there is sufficient hydrogen boil-off to completely intercept heat flow into the oxygen tank and eliminate its boil-off. Since the latent heat of vaporization of hydrogen per unit mass is more than twice that of oxygen and because there is a large cooling enthalpy available in the hydrogen boil-off, it is possible to reduce the overall boil-off mass in this way. However, the overall boil-off for a passive co-storage system is larger than the active co-storage system. The increased boil-off mass of the passive co-storage system has to be traded against the increased cooling hardware mass on the active co-storage system.

III. Design Study

Depending on the size of the propellant tanks and the mission duration there is a design point where it becomes more mass-efficient to use the active co-storage method over the passive co-storage method since in the passive co-storage method there is a significantly larger hydrogen vent rate. This paper will explore this trade in greater detail in the context of two different sized components of the lunar architecture: the Orion Service Module and the Ares V Earth Departure Stage. A broad area cooling shield was assumed as the thermal shield for the active co-storage analysis in the following design studies. For the passive co-storage model the heat load applied to the hydrogen tank was regulated to create sufficient vented hydrogen to eliminate the liquid oxygen boil-off. This can be achieved by designing the effectiveness of the heat exchange between the vented fluid and the hydrogen tank.

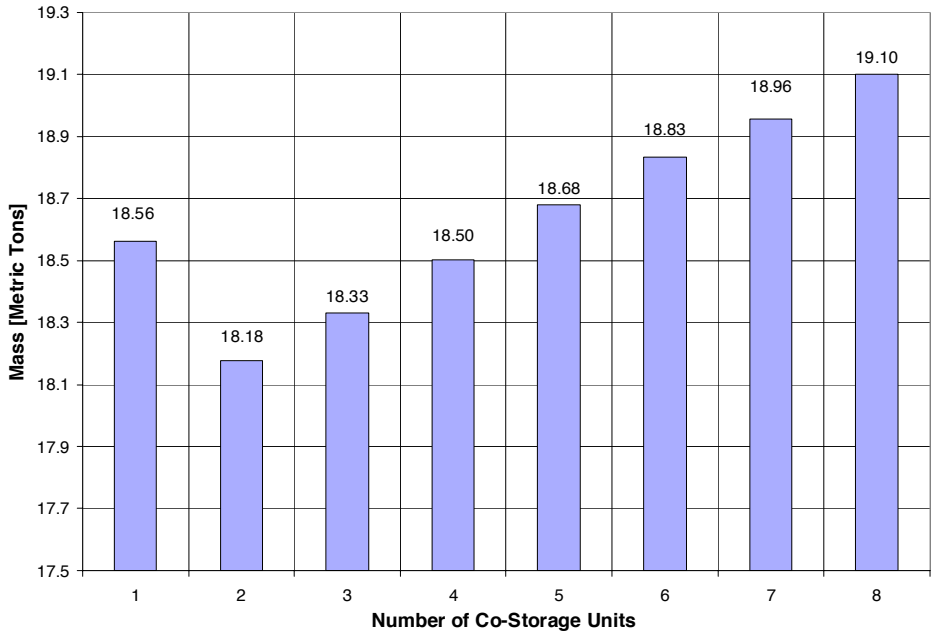


FIGURE 2. Orion wet launch mass variation with the number of active co-storage units.

The propellant tanks were modeled as thin shell Aluminum-Lithium 2195 pressure vessels designed to operate at 3 atm. These tanks had cylindrical sections capped by ellipsoidal heads. In the model for the Orion spacecraft, for a given number of units the diameter of each co-storage unit (and hence the tanks) were governed by the constraint of having to fit within the service module fairing. The diameter of the units not only affects the mass of the tanks but also affects the surface area of the tanks, which in turn affects the radiative load on the tanks. The tank diameter thus affects the the dry mass of tanks as well as the cryogen boil-off mass. These sources of mass increase feedback to the mass and volume of propellant required that ultimately again affects the diameter of the tank.[8]

The support tubes were sized to prevent axial buckling under 15g acceleration. The thickness of the support tube determined from this structural constraint determines the conductive load on the tanks through the support tube. As in the case of the tank sizing described above, the thickness of the support tubes not only affects the dry mass of the system but also the cryogen boil-off mass and these sources of mass increase feedback to the mass of required propellant that in turn results in feedback to the support tube loading and sizing. The study assumed that the support tubes were monocoque structures. Further mass benefits may be possible by using a semi-monocoque structure with internal stiffeners which would strengthen the overall structure against buckling.[9]

A spreadsheet design tool was created that iteratively converges on a co-storage design while allowing the parametric variation of the numerous constraints that govern the design of each of the components of the lunar architecture. The design tool has the capability of varying the number of co-storage units, it optimizes the shape to fit within dimensional constraints, and it computes material thicknesses based on structural requirements. The tool thus calculates the propellant mass and tank sizes for a given set of 'ΔV' and mission duration requirements, thereby providing the ability to compare the total wet launch mass and power requirements for different geometries. The tool also allows changes in the configuration of the co-storage units to account for variations in the design for the active co-storage concept and the passive co-storage concept.

A. Orion

Orion is the crew exploration vehicle that will be used to ferry astronauts to the International Space Station and it will eventually also be used for the return trip from the Moon to the Earth. The Orion liquid hydrogen/liquid oxygen propellant option was studied with active and passive co-storage options. The first part of the study evaluated the wet launch mass and dimensional requirements for different numbers of co-storage units. The constraints were determined from the Orion 606 C configuration released by the Orion Project Office in February 2008. Figure 2 shows the variation of the Orion wet launch mass with the number of active co-storage units. The co-storage units were constrained to fit inside a 5 m diameter service module. The Orion 606 C service module is approximately 2.5 m long.

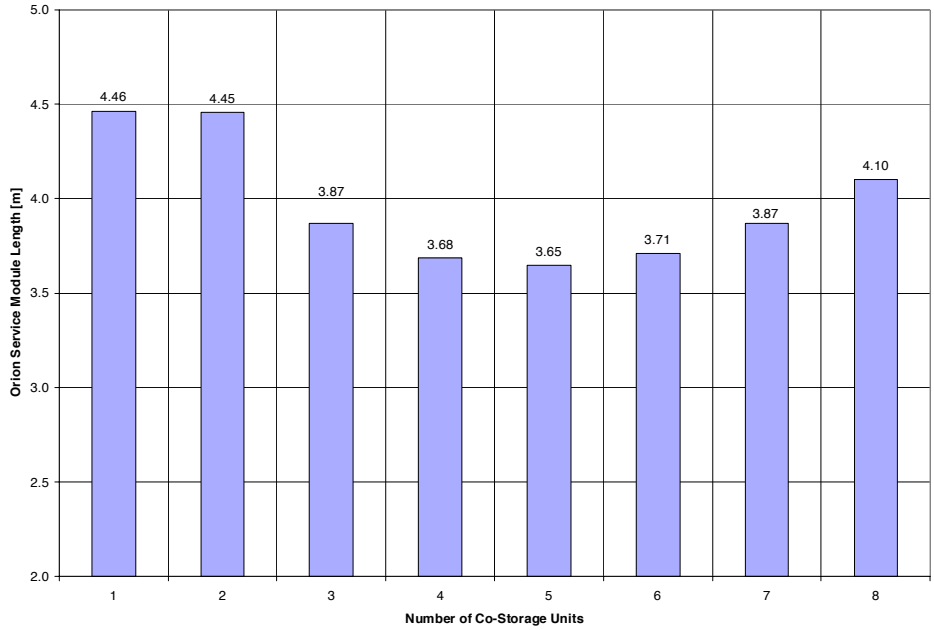


FIGURE 3. Orion service module length variation with the number of active co-storage units.

The sizing of the tanks was performed based on a 180 day lunar outpost mission. As can be expected, the low density of cryogenic hydrogen and oxygen propellants relative to the densities of hypergolic propellants will cause the tanks for these cryogenic propellants to be larger than the hypergolic tanks. In order for these tanks to fit within the 5 m diameter Orion service module the fairing would have to be longer. This analysis takes into account the extra mass of fairing required when various configurations of these longer cryogenic propellant tanks are used.

The 2 co-storage unit configuration will provide the minimum mass configuration of 18.2 metric tons for this mission. However, the 2 co-storage unit configuration will have fairing that is 4.5 m long. A four co-storage unit configuration will have a mass of about 18.5 tons but it will fit within a 3.7 m fairing. Figure 3 shows the variation of length with the number of co-storage units.

As can be seen by comparing figures 2 and 3, the optimum mass Orion Service Module and optimum length Orion Service Module have different co-storage configurations. A 4 co-storage unit configuration allows a compromise between the launch mass and the length. Figure 4 depicts the arrangement of a four co-storage unit in an Orion service module. Each co-storage unit in the 4 unit configuration has a diameter of 1.7 m. This

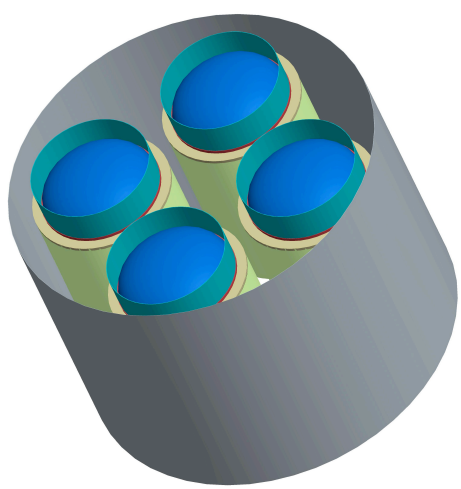


FIGURE 4. A 4 unit co-storage configuration in a lunar Orion service module.

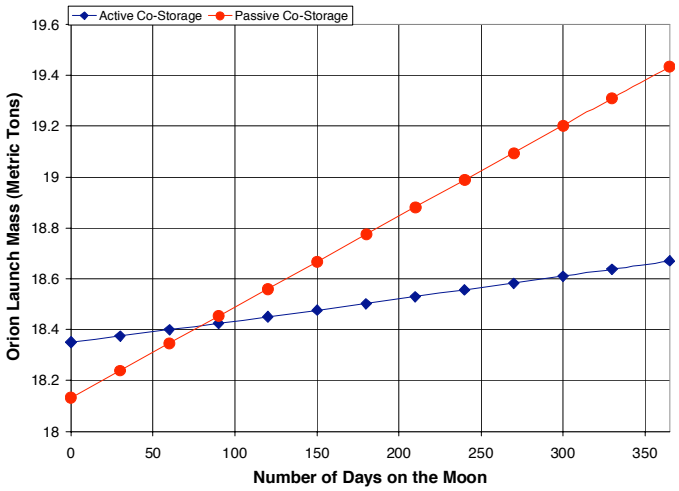


Figure 5. Variation of the lunar Orion launch mass with mission duration for the active and passive options.

configuration also allows a 1.2 m diameter space between the tanks for a central thrust tube.

The goal for an outpost mission is to have a human presence on the lunar surface for 180 days. During this period of time the Orion will be orbiting the moon. Figure 5 shows the variation of the Orion wet launch mass with mission duration for the passive co-storage, and active co-storage systems. When the mission duration is longer than 79 days the active co-storage on Orion is more mass efficient than a passive co-storage system.

B. Ares V Earth Departure Stage

In order to investigate the effect of scaling co-storage systems on a larger scale system, a similar analysis was performed for the Ares V Earth Departure Stage (EDS). The EDS is the upper stage of the Ares V launch vehicle that will launch the Altair and the Orion towards the moon. The mission plan as of May 2008 is for the Ares V to have enough extra propellant on the EDS such that the mission can be completed in spite of the propellant that boils off during a 4 days LEO loiter by the EDS and the Altair. The Ares I carrying the Orion will have to dock with the EDS and the Altair within this time frame for the mission to be successful. This quick-launch requirement leads to very complex launch pad demands. A co-storage concept can help to relax this 4 day constraint significantly. Figure 6 shows the variation of EDS launched mass with the number of days of LEO loiter. When the mission duration is longer than 69 days, an EDS with an active co-storage system is more mass efficient than one with a passive co-storage system. It is significant to note that a 3 ton active co-storage launch mass (which includes the active co-storage hardware mass and the corresponding required extra propellant and storage mass) out of a total EDS launched mass of 260 tons enables the relaxation in the number of LEO loiter days from 4 days to 365 days.

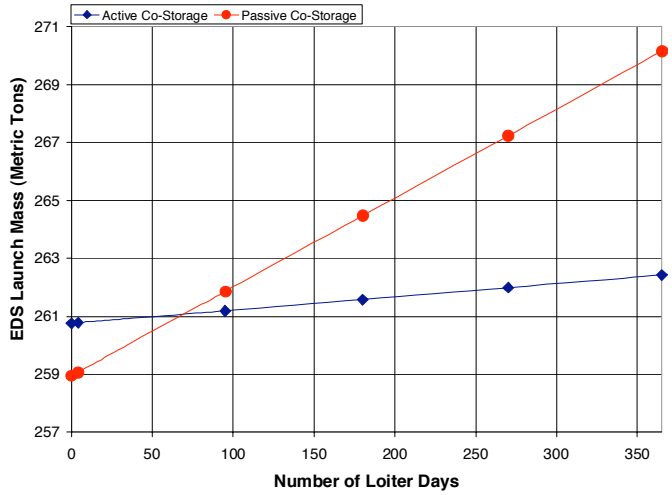


Figure 6. Variation of the EDS launch mass with LEO loiter duration for the active and passive options.

IV. Conclusions

A study on the system level impact of cryogenic co-storage on the lunar architecture is presented. The models for the Orion and Ares V EDS indicate that the passive co-storage option is less massive for shorter duration missions, but as the mission durations become longer the active co-storage concept becomes substantially more mass efficient. The cross-over time where an active co-storage configuration with broad area cooling becomes more mass efficient than a passive configuration is 79 days for the Orion spacecraft and 69 days for the Ares V EDS. The EDS number in particular highlights the benefit of using active co-storage with BAC over active co-storage with self-supporting shields. The cross-over time for an EDS with active co-storage using self-supporting shields was previously found to be about 355 days[10].

Acknowledgments

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