47th International Conference on Environmental Systems
16-20 July 2017, Charleston, South Carolina

ICES-2017-333

An Alternative Approach to Human Servicing of Crewed Earth Orbiting Spacecraft

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As crewed spacecraft have grown larger and more complex, they have come to rely on spacewalks, or Extravehicular Activities (EVA), for assembly and to assure mission success. Typically, these spacecraft maintain all of the hardware and trained personnel needed to perform an EVA on-board at all times. Maintaining this capability requires up-mass, volume for storage of EVA hardware, crew time for ground and on-orbit training, and on-orbit maintenance of EVA hardware. This paper proposes an alternative methodology, utilizing either launch-on-need hardware and crew or regularly scheduled missions to provide EVA capability for space stations in low Earth orbit after assembly complete. Much the same way that one would call a repairman to fix something at their home these EVAs are dedicated to maintenance and upgrades of the orbiting station. For crew safety contingencies it is assumed the station would be designed such the crew could either solve those issues from inside the spacecraft or use the docked Earth to Orbit vehicles as a return lifeboat, in the same manner as the International Space Station (ISS) which does not rely on EVA for crew safety related contingencies. This approach would reduce ground training requirements for long duration crews, save Intravehicular Activity (IVA) crew time in the form of EVA hardware maintenance and on-orbit training, and lead to more efficient EVAs because they would be performed by specialists with detailed knowledge and training stemming from their direct involvement in the development of the EVA. The on-orbit crew would then be available to focus on the immediate response to any failures such as IVA systems reconfiguration or jumper installation as well as the day-to-day operations of the spacecraft and payloads. This paper will look at how current unplanned EVAs are conducted on ISS, including the time required for preparation, and offer an alternative for future spacecraft. As this methodology relies on the on-time and on-need launch of spacecraft, any space station that utilized this approach would need a robust transportation system, possibly including more than one launch vehicle capable of carrying crew. In addition, the fault tolerance of the future space station would be an important consideration in how much time was available for EVA preparation after the failure. Ideally the fault tolerance of the station would allow for the maintenance tasks to be grouped such that they could be handled by regularly scheduled maintenance visits and not contingency launches. Each future program would have to weigh the risk of on-time launch against the increase in available crew time for the main objective of the spacecraft. This is only one of several ideas that could be used to reduce or eliminate a station's reliance on rapid turnaround EVAs using on-board crew. Others could include having shirt-sleeve access to critical systems or utilizing low pressure temporarily pressurized equipment bays.

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Nomenclature

CCP = Commercial Crew Program
EMU = ExtraVehicular Mobility Unit
EVA = ExtraVehicular Activity
GGR&C = Generic Ground rules, Requirements and Constraints
HST = Hubble Space Telescope
IDRD = Increment Definition and Requirements Document
ISS = International Space Station
LEO = Low Earth Orbit
MA/ITP = Multilateral Advanced/Increment Training Plan
MMOD = MicroMeteoroid / Orbital Debris
mSv = millisievert, unit of radiation dosage
NASA = National Aeronautics and Space Administration
NBL = Neutral Buoyancy Laboratory
STS = Space Transportation System
USOS = United States On-orbit Segment

I. Introduction

HISTORY has shown that having repair capabilities for a spacecraft that is in low-Earth orbit (LEO) for extended periods of time is vital to maintaining functionality and even habitability. Three historical examples provide a good overview of the different reasons a spaceflight program needs EVA capability. During the launch of Skylab in May 1973 a MicroMeteoroid / Orbital Debris (MMOD) shield was torn loose due to aerodynamic loads. The shield caused one solar array to be lost and one trapped such that it could not be deployed remotely. The three man crew of Skylab I that launched 11 days later were trained on the ground how to release the stuck solar array and deploy a thermal shield so that the Skylab missions could continue.[1] Since this repair was due to ascent damage and not the failure of a component designed for replacement, training the crew on the ground prior to launch would allow for the engineers designing the repair to talk directly to the crew increasing the efficiency of the training and not impacting the conduct of the primary mission with additional training and studying. The damage made Skylab uninhabitable and required hardware to be launched from the ground for the repair. If a crew had been at Skylab shortly after its launch they likely would have had to evacuate to the return capsule at least temporarily. The five Hubble Space Telescope (HST) repair missions flown by Space Shuttle crews allowed for the repair and upgrade of the telescope from its launch in 1990 through the final Shuttle servicing mission in 2009.[2] These missions have shown the advantage of using highly trained crews on highly choreographed missions to maximize the productivity of on-orbit repair. Over the course of these missions new science instruments were installed, old instruments were repaired in ways never conceived by their designers, and the telescope's utilities were upgraded with newer technology. The first HST servicing mission was used to correct for an optics error that greatly diminished the telescope's capabilities. The final example is the 2010 replacement of an ISS external thermal control pump.[3] The pump drove one of two main thermal loops on the US side of the ISS. Loss of the other loop would have required powering down all portions of the ISS except the Russian Segment, so there was a high priority on completing this repair due to the fault tolerance of the system. Due to this priority, the first spacewalk (also known as extravehicular activity [EVA]) was able to occur approximately one week after the failure and the new pump was up and running a little over two weeks after the original failure. In this repair scenario it was critical to have EVA trained crew already on-board who could react quickly.

A program can work to minimize the need for extravehicular repairs by designing fault tolerance and redundancy into the spacecraft systems, making hardware accessible inside a pressurized atmosphere, and utilizing robotic operations, but unexpected failures in the past have demonstrated the need for robust and flexible capability to perform repairs with spacewalking astronauts. Spacewalks are an important component to assure the health and use of the ISS for research and operations, but they are time- and resource-consuming, put the crew at increased risk as compared to IVA tasks, and the EVA hardware requires on-orbit maintenance and takes up space on cargo vehicles and storage space inside the pressurized modules. This paper utilizes the current methods on the ISS as the baseline for comparison to alternative methodologies.

Since one cannot predict all the possible repairs or upgrades that will take place during a crew's stay, ISS EVA training has pivoted to focus on skills-based training for EVA, rather than the task-based training conducted for the Space Shuttle program and ISS assembly. Therefore, larger amounts of on-orbit crew time are devoted to studying and preparing for a specific upcoming EVA, and increased inefficiency during a spacewalk has to be accounted for, due to the lack of rehearsing for a specific task.

Ground launched EVA capabilities would provide a space station program the opportunity to reduce on-orbit EVA hardware maintenance and stowage, as well as reduce mission training for the astronauts to allow them to focus on science and internal vehicle repairs and save on-orbit crew time that would otherwise be used to prepare for upcoming spacewalks. If launch vehicles can prove to be available on short notice, launch-on-need EVAs would be an additional benefit over and above using regularly scheduled launches for maintenance and repair. As the National Aeronautics and Space Administration's (NASA) Commercial Crew Program (CCP) ramps up, companies like SpaceX and Boeing are working to develop safe, reliable, cost-effective access to and from low-Earth orbit.[4] The assertions made by these companies will of course have to be borne out by actual operational missions. This paper provides an overview of how ground launched EVA capabilities could be an alternative for future space mission design architectures once the required launch capabilities are in place.

II. Background of Current EVA Operations

During the assembly of the ISS, the majority of spacewalks were conducted by visiting Space Shuttle crews. These crews not only assembled the ISS but took care of repairs that could wait for a planned mission to fly. A Shuttle crew headed to the ISS would typically consist of seven crewmembers and the mission would last for approximately two weeks. This allowed the crew to specialize in the various tasks of the mission increasing their proficiency. The EVA crew would train for approximately one year prior to flight and would practice each spacewalk at least three and up to seven times resulting in about twenty Neutral Buoyancy Laboratory (NBL) training runs specific to that mission. In addition these crews had the opportunity to see much of the hardware they would install prior to launch and could directly ask questions of the engineers who were the experts. In addition to being mentally demanding, spacewalks are also incredibly physically demanding where crew can be sealed in their spacesuits for ten hours or more with only 32 ounces of water and no food. The short duration of the Shuttle mission allowed the crew to workout a great deal prior to launch and to perform their spacewalks without some of the longer term impacts of weightlessness. Spacewalks are choreographed in the NBL and since the environment and hardware in the NBL are not a perfect analog of spaceflight, adjustment factors are required to ensure that the spacewalk will take place within the life support capabilities of the spacesuit. For Shuttle crews this adjustment factor was typically 1.2. In other words a task during an actual spacewalk would be estimated to take twenty percent more time than it did in the NBL. For ISS crews this factor is typically greater indicating a loss of efficiency.

As the Space Shuttle program ended, ISS crew members were relied on to perform all EVA maintenance, upgrades, and repairs. Since an ISS crewmember is preparing for a six month mission versus the two weeks of a Shuttle crewmember and the United States On-orbit Segment (USOS) has a crew of three versus the Shuttle's crew of seven the ISS crew has to be trained on a broader list of topics tending to make them more generalists than their Shuttle counterparts. Due to this NASA has shifted its EVA training model from a task-based focus to a skills-based focus.[5] For task-based training, the crew practices the specific timeline that they want to execute on-orbit multiple times prior to launch. A skills-based approach focuses not on a specific EVA timeline, but rather on the generic skills needed to perform any manner of spacewalks that might occur during an ISS expedition. Without the detailed focus on a particular task, inefficiencies have to be accounted for, and could sometimes mean that a given repair could take more EVAs to complete than under task-based training. The ISS crew training flow is 18-24 months over which the crew will receive nine NBL runs which cover any tasks that are known before they launch as well as the generic ISS maintenance tasks that could be required but would not be known until after launch. This means that the ISS crews receive approximately half the NBL runs of a Shuttle crew during a training template almost twice as long. Due to this, the adjustment factor for an ISS crew EVA is 1.5 or fifty percent longer than the NBL time which is a twenty-five percent increase in the number of EVAs required for a given amount of work. Reducing the number of EVAs that the crew must perform would reduce the risk to the EVA crew, the amount of consumables (oxygen & water) and crew time used. Each ISS EVA currently uses approximately 3 lbs. of air that can't be reclaimed by the depress pump, 15 lbs. of oxygen for the prebreathe protocol and 12 lbs. of water for the two spacesuits. In addition to the consumables used, the generic template of crew time required for the preparations and execution of an ISS crew EVA is 124 hours. Two EVAs in series currently uses 193 hours of crew time, meaning that each ISS EVA saved, due to the efficiency of the EVA crew or other factors, could save 69 hours of crew time.[6]

Even when not performing EVAs on ISS there is a cost in crew time, stowage volume, ISS consumables, and upmass/downmass to maintain the capability to perform EVAs when desired. The USOS maintains four spacesuits at any given time along with batteries and other ancillary hardware requiring maintenance.

III. Launch-On-Need Methodology

As spacecraft advance and space travel hopefully opens up to a wider portion of the population, training and skill sets will need to accommodate specialists. This can be done either through larger crews on the stations or by outsourcing some of the more specialized skills such as EVA. A ground launched EVA approach would allow the crew or passengers to stay focused on the purpose of the orbital facility, whether it is scientific payloads, orbital manufacturing or recreation, while highly trained EVA-specific astronauts could attend to repairs. Depending on both the fault tolerance of the station and the severity of the failure this could either mean regularly scheduled maintenance missions or launch-on-need crews. The full implementation of the launch-on-need orbital repair is still a long way off due to the need for routine reliable crew launch however it is expected that incremental advances could be made on outposts in LEO going forward. The most basic form of this methodology would be to have regularly scheduled logistics flights that would provide a surge capability for a limited subset of EVA or IVA tasks to augment the on-orbit crew. Before the mission, the designated EVA crewmembers will keep up their EVA proficiency skills with neutral buoyancy runs and recurrent training. Once a set of mission objectives has been identified, these EVA crewmembers will transition from performing proficiency training into performing two or three dedicated, specific training runs per EVA to develop and practice the specific tasks prior to launch and on-orbit execution. During this time, the specific tools and hardware, selected from the standard complement of hardware assuming this is hardware designed for repair, will be prepared and manifested on the launch-on-need vehicle. If an unplanned type of repair is required, additional time to develop and manufacture the hardware may be needed. After launch and rendezvous with the vehicle requiring repairs, the launch-on-need crew will perform the repairs with the hardware, tools, and suits that launched along with them. This model will eliminate on-orbit maintenance, repairs, inspections or re-configuration of space suits on-orbit. During this time, the long-duration crew members on-orbit will continue to perform as much of their standard duties as possible, thus maximizing the usefulness of the vehicle, even when repairs are needed or in progress. In the most extreme version of this example the launched spacecraft could even be used as the airlock eliminating the need for that hardware on the station. The station to be repaired would still require EVA compatibility in the form of translation aids and EVA replaceable hardware.

IV. Comparison and Discussion

To determine the impacts and feasibility of a launch-on-need approach to EVA repairs, as opposed to the current methodology, it is valuable to compare the approaches in their many facets. Not only will cost play a major factor, but also things such as crew health, training time, risk and schedule flexibility will also impact a program's decision on how to perform EVA repair. While a cost comparison can clearly be weighed by simply looking at numbers such as an annual cost, or a cost per event, in this study, a strategy comparison will simply offer tradeoffs that each program will have to weigh differently depending on its mission architecture to decide how much of the EVA capability they can hand off to visiting crew.

A. Strategy Comparison

A launch-on-need operation would reduce the need for pre-flight training of long-duration crew members or would allow more time in the training flow to be dedicated to the primary mission of the vehicle. Outsourcing the EVA capability would also save on-orbit crew time and stowage space for suits, tools, maintenance equipment, and spare parts, and reduce overall radiation exposure to the long-duration crew.

Prior to launch, an assigned long-duration ISS crew member receives training on generic EVA knowledge and skills to prepare for any host of maintenance tasks and repairs that could be needed on-orbit. The current estimate of that training time is over 229 hours[7] over the two years leading up until the mission. This number has been reduced over the years to try and shorten the training flow and increase knowledge retention. In addition as in any profession when practitioners are able to specialize they become more efficient and skilled than the general population potentially further reducing the number of EVAs for any given repair as shown with the comparison to Shuttle era adjustment factors. Annually EVA hardware requires over 54 hours of on-orbit crew time[8] to perform nominal maintenance in addition to approximately 60 lbs. of water and 12 lbs. of oxygen for the standard complement of 4 EMUs. Preparation for a single ISS based US EVA takes at least 124 crew hours including preparing the suits and refresher training for the crew. For a complex EVA this goes up as they need more time to review the EVA timeline. This time does not include any remediation or preparation of the spare hardware before it is taken EVA. Some of this crew time could be reduced by the development of an EVA system of hardware specifically designed to reduce maintenance, however developing a new spacesuit alone has been estimated at $180 million.[9] In addition until the new suit is developed and implemented on a future station the savings would not be certain as several of the current EMU maintenance activities are the result of lessons learned through monitoring the hardware throughout the program.

Astronauts on a six month mission to ISS receive radiation doses of 100 mSv,[10] which is about 300 times the dosage for an average American.[11] Crew members receive additional radiation doses during spacewalks,[12] potentially limiting future spaceflight opportunities for an ISS crew, whereas a launch-on-need crew could perform multiple spacewalks at higher radiation levels, but stay under a lifetime radiation limit by not staying on-orbit for long durations.

B. Cost Comparison

Costs can be measured in time, efficiency, and dollars. For a cost comparison the ISS will serve as our baseline. Based on the 2014 OIG report, NASA intends to spend $3-4 billion per year on ISS between 2014 and 2024.[13] This is NASA's recurring cost and does not reflect the initial investment to build the ISS or the recurring cost to the international partners. If we included the assembly costs we would have to decide on an end date of ISS to amortize that cost over. Also since we are talking about operational cost for US EVAs we will only use the US recurring cost. Assuming 5 US crew per year each staying 180 days (6 months) yields a cost/day/US crewmember cost of $3.9 million. The ISS crew has a workday of 6.5 hours equating to a cost of $600,000 per work hour. The rest of their day is filled with exercise, meals, and sleep. Using ground launched EVA crew with their own complement of hardware would save roughly 124 hours of crew time for one EVA which could be dedicated to other research or operations equal to $74.4 million using the baseline ISS cost without accounting for the extra efficiency of the ground launched crew. The standard efficiency adjustment for an ISS-based EVA is fifty percent, whereas EVA-expert crew members in the Space Shuttle era operated with only a twenty percent adjustment factor.[13] A similar efficiency factor can be assumed for ground launched EVAs as for Space Shuttle EVAs which would lead to them needing to perform 20 percent fewer EVAs. There are efficiencies to be gained in crew time for performing multiple EVAs together so we will only take credit for the additional crew time to perform a second EVA in a series which is 69 hours. Therefore, if a ground launched crew were used on a consistent basis and were able to save an additional EVA over the course of time, this would be a potential savings of an additional $41.4 million per EVA saved. All of these savings vary considerably based on the spacing, timing, and content of the EVAs. It is also understood that these are not true costs saved, since the long duration crew would still be there. However, this is in an attempt to show the value that the ground launched team adds to the mission.

A future station which is able to eliminate the on-board maintenance of EVA hardware by relying fully on ground launched EVA capability would cut an additional 54 hours annually which equates to $32.4 million. Additionally there would not be a need to launch EVA hardware to the future station reducing launch costs although this would be partially offset by the need to launch a subset of this hardware with the EVA crew. The launch costs could be a true savings as this would allow for fewer resupply missions although this could be offset by the additional science hardware that would need to be manifested to occupy the crew's time. These costs only measure that portion of on-orbit crew time used directly for maintenance. They do not include the time it takes for on-orbit crew members to pack and unpack EVA hardware from visiting vehicles or the costs of having flight controllers and engineers available for mission support during on-orbit EVA hardware maintenance conducted IVA.

For the cost comparison table below we will assume a 3 EVA mission. This is on the lower end of what Shuttle missions to ISS were performing during the end of ISS assembly, so this example would be comparable to scheduled mission for repairs and upgrades. To complete the same amount of EVA work as the ground launched crew would require 3.75 EVAs by an on-orbit crew. A launch-on need mission could comprise of anywhere from 1 to 4 EVAs.

	Current ISS model	**Launch-on-need**	**Difference**
On-orbit EVA execution for 3 EVAs	262 crew hours (40 crew days) of lost operations at $3.9M/day	No lost crew time on ISS	$157.2M
Additional EVA due to inefficiencies	0.75 * 69 crew hours (8 crew days) at $3.9M/day	No lost crew time on ISS	$31.1M
Annual On-Orbit EVA maintenance	54 crew hours (8.3 crew days) at $3.9M/day	Still required if desired to maintain EVA capability on station	$32.4M
Launch on-need break-even costs			**$188.3M to $220.7M**

Table 1. Cost Breakdown. *Comparison of costs for the current ISS architecture and the launch on-need approach.*

C. Risk

The loss of crew risk during a USOS EVA is a function of the number of EVAs conducted. Since in the previous example, a 3 EVA ground launched mission would accomplish the same amount of work as 4 EVAs from a long duration crew, the 4 EVA LOC risk would be the baseline. While there would be a reduced EVA risk it is acknowledged that the risk of the launch and return would be added for the ground launched crew and though that risk could not be spread over a longer on-orbit time which would reduce its impact on the overall mission risk, the long duration crew would be more productive than they would if they had to conduct the EVAs. In addition to crew risk the added time to complete a repair would require the station to have more robust redundancy for critical systems to allow for the full implementation of this concept.

D. Drawbacks and Limitations

A major limitation of the launch-on-need EVA plan, is that it assumes there is a reliable, regular launch availability to the orbiting vehicle. ISS critical contingency EVAs are conducted to replace external components that were deemed critical enough to need rapid repair or replacement by contingency spacewalk within two to four weeks of failure.[14] This would indicate that rapid launch-on-need capability would not be suitable in the short term for a vehicle such as ISS. However it could still be useful for complex repairs that require complex choreography.

V. Conclusion

Assuming a government or private entity can develop a launch-on-need capability to be ready to launch a vehicle with only a two to four week notice or develop a station with sufficient fault tolerance to allow for scheduled EVA missions, the cost savings and/or the science that would continue on an orbiting laboratory could prove to be extremely valuable and advantageous when developing or re-evaluating a mission architecture. As calculated above, this methodology could add $74.4M to 220.7M in capability for the primary mission as well as reduce logistics for the primary mission. An estimate for the commercial crew program was $58M per seat which would work out to $232M for the entire four crew mission.[15] In addition, hardware and spacesuits that have proven to require significant maintenance and repair on-orbit can be serviced by ground technicians and working at peak performance for a ground launched EVA.

Acknowledgments

The authors of this paper would like to specifically thank Amie Cantilo for guidance on EVA hardware being launched, Nicholas McHugh for EVA stowage, Megan Murphey and Bridget Scheib for crew training plans, Lawrence Thomas for on orbit crew time, and the MAPI PRA team for their assistance with this paper.

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