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 mission success and crew safety. 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 volume and up-mass 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 launch on-need hardware and crew to provide EVA capability for space stations in Earth orbit after assembly complete, in the same way that one would call a repairman to fix something at their home. This approach would reduce ground training requirements, 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 the failure as well as the day-to-day operations of the spacecraft and payloads. This paper will look at how current unplanned EVAs are conducted, including the time required for preparation, and offer alternatives 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 including more than one launch vehicle capable of carrying crew. In addition, the fault tolerance of the space station would be an important consideration in how much time was available for EVA preparation after the failure. 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.

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

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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 so that the Skylab missions could continue.[1] Since this repair was due to ascent damage and not the failure of 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 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 telescopes 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 International Space Station (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 this priority the first spacewalk (also knowns as extravehicular activity [EVA]) was able to occur 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, flexible, and timely repairs by 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, increase risk to the crew, and the hardware requires on-orbit maintenance and takes up valuable space on cargo vehicles and storage space inside the pressurized modules.

Since one cannot predict all the possible repairs that will take place during a given mission, ISS EVA training has pivoted to focus on skills-based training for EVA, rather than task-based training. Therefore, larger amounts of on-orbit crew time are devoted to studying and preparing for the specific upcoming EVA, and inefficiencies during a spacewalk have to be accounted for due to the lack rehearsing a specific choreography.

Launch on-need EVA capabilities would provide a spaceflight program the opportunity to reduce on-orbit EVA hardware maintenance and stowage, as well as reduce mission training for the astronauts 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 can be cost effective and more efficient than the current EVA operations. As the National Aeronautics and Space Administration's (NASA) Commercial Crew Program (CCP) ramps up, companies like SpaceX and Boeing are developing safe, reliable, cost-effective access to and from low-Earth orbit.[4] This paper provides an overview of how launch-on need EVA capabilities could be a viable 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 maintenance 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 would allow 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 would have 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 would allow 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 which is one of the largest pools in the world. Since the environment and hardware in the NBL are not a perfect analog of spaceflight adjustment factors are required to ensure that the spacewalk is timeline to 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.

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. The ISS crew training flow is 18-24 month 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. The generic template for an ISS crew EVA involves 124 hours of crew crew time and two back to back EVAs costs 193 hours of crew time meaning that each ISS EVA saved due to the efficiency of the EVA crew alone could save 69 hours.[6]

Even when not performing EVAs on ISS there is a cost in crew time, stowage volume, and upmas/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

When a scientist is asked to work in a laboratory and the air conditioner breaks, the scientist isn't asked to fix it! Instead a professional repairman is called to attend to the facility issue. Similarly, a launch on-need approach would allow the crew 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. The full implementation of launch on-need orbital repair that will be discussed here 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. Before the time of an external failure, the two designated launch on-need crewmembers will keep up their EVA proficiency skills with NBL runs multiple times each month. At the time of failure, these EVA crewmembers will transition from performing NBL proficiency runs into performing two or three dedicated, specific NBL runs to work on the repairs prior to launch and on-orbit execution. During this time, the specific tools and hardware that will be needed for the repairs will be prepared and manifested on the launch on-need vehicle. 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, thus not requiring on-orbit maintenance, repairs, inspections or configuration. During this time, the long-duration crew members on-orbit will continue to perform as much science as possible, thus maximizing the usefulness of the vehicle, even when repairs are needed or in progress.

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, facility usage, 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.

A. Strategy Comparison

A launch on-need operation would significantly reduce the need for pre-flight training of long-duration crew members, save on-orbit crew time and stowage space for suits, tools, and maintenance equipment, 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. During the mission, EVA hardware requires over 54 hours of on-orbit crew time[8] to perform annual maintenance.

A smaller pool of launch on-need qualified crew members would require fewer spacesuit components and likely fewer sizes to be maintained by a team of professionals on the ground. Currently, the Extravehicular Mobility Unit (EMU) program protects suit sizing to accommodate a 5th percentile Japanese female height and weight, all the way up to a 95th percentile Air Force male.[9] Reducing the number of component sizes as well as the quantity could drastically reduce the project maintenance and life cycle costs.

Astronauts on a six month mission to ISS receive radiation doses are 100 mSv.[10] Crew members could receive higher doses during spacewalks,[11] 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. The amount of time saved is roughly 124 hours, plus 54 hours of annual maintenance of hardware, which equates to 178 hours minimum on-orbit at $7.5 million/crew/day,[12] or over $55 million. In addition, 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 assume for launch on-need EVAs as for Space Shuttle EVAs. Therefore, if a launch on-need crew was efficient enough to save an additional EVA from having to be performed, it was save an additional 69 hours, or $21.5 million.

These costs only measure that of on-orbit crew time. They do not include the time it takes for on-orbit crew members to pack and unpack EVA hardware from visiting vehicles, the time spent on ground training, or the costs of having flight controllers and engineers available for mission support during on-orbit EVA maintenance.

	Current ISS model	**Launch on-need**	**Difference**
On-orbit EVA execution	124 hours of lost science at $7.5M/day	No science lost on ISS	$38.75M
On-Orbit EVA maintenance	54 hours of lost science at $7.5M/day	No science lost on ISS	$16.88M
Additional EVA due to inefficiencies	69 hours of lost science at $7.5M/day	No science lost on ISS	$21.85M
Ground training	229 hours x 12 crew/year	229 hours x 4 crew/year	1,832 hours x $215K/yr (real employee cost[14]) = $189K
EVA Operations team	45 employees	15 employees	30 employees x $215K/yr =$6.45M
Facility costs	$20M/year[15]	33% usage, or ~$6.5M/year	$13.5M
Launch on-need break-even costs			**$97.62M**

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

Ground training for long-duration crew members take not only a large team of employees, but also lots of facility scheduling time. Rather than have twelve crew members going through Increment training at any given time, the instructors could focus training on four launch on-need crew members and drastically cut down on facility usage, down to as much as one-third the use, allowing for the space to be rented or leased at other times. Additionally, without as many crew members to train, the operations team does not need as many instructors, limited the need to staff a full flight control team during on-orbit repairs, about 15 team members, that would more than suffice to cover any training needs during non-flight timeframes.

C. 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. A ISS critical contingency EVA, external component types that were deemed

critical enough to need rapid repair or replacement by contingency spacewalk, must happen within two to four weeks of failure.[16] Therefore, a vehicle must be ready to launch on short notice for a launch on-need scenario.

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, the cost savings and the science that would continue on an orbiting laboratory would prove to be extremely valuable and advantageous when developing or re-evaluating a mission architecture. As calculated in Table 1, the breakeven price of these launch-on need programs would be a approximately $97.62M. Considering that companies like SpaceX are currently quoting $62M for a 2018 launch of their Falcon 9, the price very likely is already within reason today.[17] In addition, hardware and spacesuits that have proven to require significant maintenance and repair times on-orbit can be serviced by ground technicians and working at peak performance for a launch on-need EVA.

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