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Single-Person Spacecraft Favored for Gateway EVA

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It is assumed that astronauts need space suits to go outside. However, the Single-Person Spacecraft (SPS) allows extravehicular activity (EVA) not only without suits, but without an airlock. NASA is planning on building a Lunar Orbital Platform-Gateway and most concepts include suited astronauts with an airlock. Is traditional suited EVA the only solution or is the SPS a credible alternative? To answer this question, an engineering tradeoff analysis was conducted comparing the two options. Findings reveal that the SPS is favored because it is safer, more efficient, weighs less, and significantly reduces the cost to the government. Furthermore, it requires fewer launches, has less of an impact on elements, and fulfills NASA's stated objectives for the Gateway.

Nomenclature

EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
GCR = Galactic Cosmic Ray
GN2 = Gaseous Nitrogen
ISS = International Space Station
IDBM = International Docking Berthing Mechanism
LCVG = Liquid Cooling Ventilation Garment
LEO = Low-Earth Orbit
MAG = Maximum Absorbency Garment
MMOD = Micrometeoroid/Orbital Debris
MMU = Manned Maneuvering Unit
PSI = Pounds per Square Inch
SAFER = Simplified Aid For EVA Rescue
SPE = Solar Proton Event
SPS = Single-Person Spacecraft
SLS = Space Launch System
WEI = Work Efficiency Index
WIF = Worksite Interface

I. Introduction

NASA's Lunar Orbital Platform-Gateway (Figure 1) is an exploration waypoint comprised of a habitat, power bus, airlock module, and docking ports. NASA created a reference configuration then awarded contracts to six companies for developing their own concepts. The intent of these early contracts is to encourage new and creative ways of achieving NASA's overall Gateway objectives. For the most part this approach seems to have worked because

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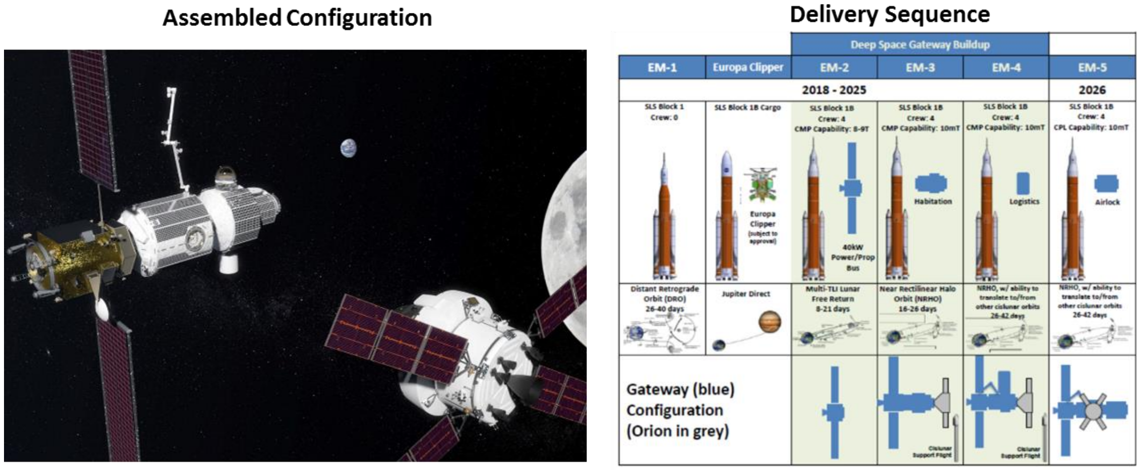

Figure 1. NASA's Lunar Orbital Platform-Gateway Configuration and Delivery Sequence.

contractors are showing configurations with rigid and inflatable habitats, new and repurposed hardware, even different propulsion systems. Missing are creative alternatives for Gateway EVA. This is important because conventional suited EVA has a significant impact on design, mass, cost, delivery flights, and operations. The Single-Person Spacecraft (SPS) is an alternative for Gateway EVA, but how does it compare with conventional suited operations? In order to assess the differences, a trade study using eight figures of merit was conducted and this paper provides summary of the analysis and findings.

II. Gateway EVA Options

First, a note about the trade options. There are three EVA options for the Gateway; 1. Use the existing ISS space suit, 2. Build a new space suit, or 3. Use a Single-Person Spacecraft (Figure 2). For the purpose of this trade, there is

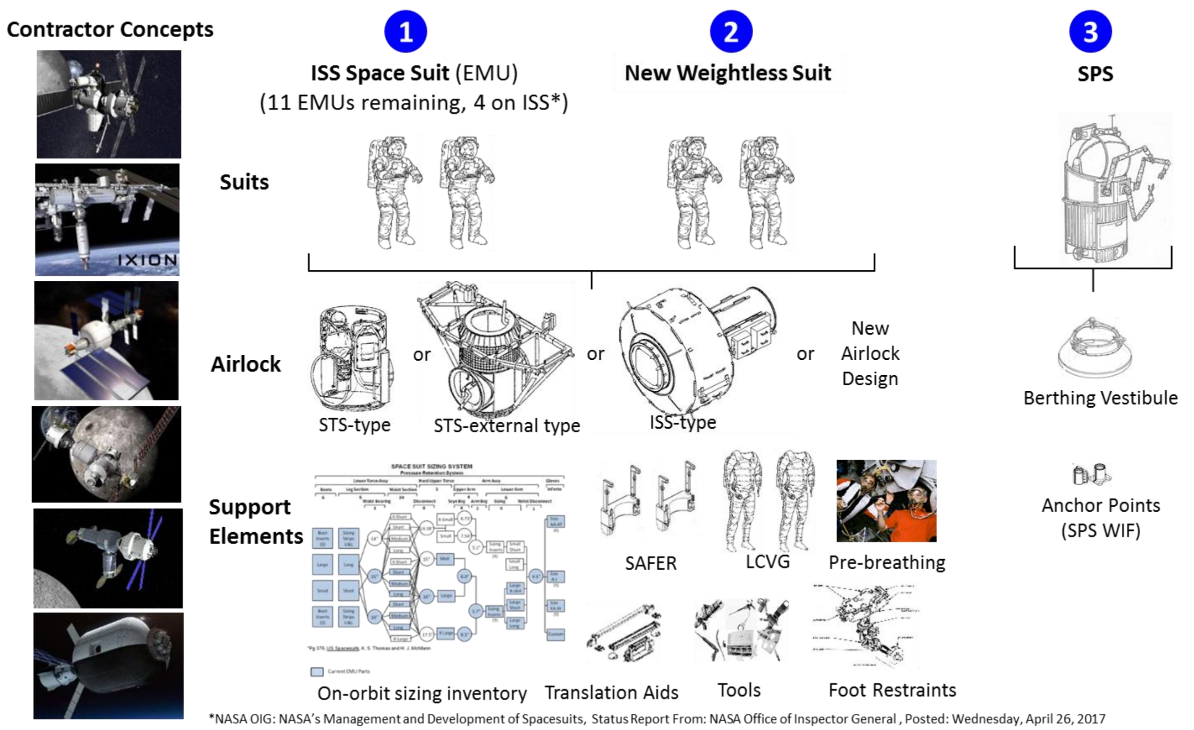

Figure 2. Three Options for Gateway EVA with Necessary Support Equipment.

negligible difference between using the ISS suit and a new suit; both require an air lock for access to space, pre-breathing to avoid getting the "Bends," and are equipped with SAFERs (Simplified Aid for EVA Rescue). Therefore, the trade compared a Gateway designed for pressure suited EVA to one configured for SPS operations.

III. Summary Findings

The intent of this trade is to be as thorough as possible addressing all aspects of Gateway EVA. Consequently, there is a large amount of material to be presented. However, rather than make the reader plow through the 44 comparisons before understanding the results, a summary is presented up front (Figure 3) followed by a compressed discussion of comparative assessments.

The results strongly favor the SPS. This is not as unreasonable as it looks because the SPS is specifically designed to improve weightless EVA. Both the ISS suit and a new suit are solutions constrained by the fundamental characteristics of pressure suit operations. For the Gateway, the SPS trades well because it is not a suit but a small

Safety	Suited Gateway	SPS Gateway
Bends		
Fire Risk		
Fire Control		
Water inside		
Radiation (SPE)		
Out of breathing gas		
Breathing gas leak		
Suit Trauma		
Fatigue		
Micrometeoroid		
Astronaut Set Free		
Out of propellant		
Mass		
Shuttle Airlock EVA/1 SPS		
ISS Airlock EVA/2 SPSs		
Efficiency		
Work Efficiency Index		
Translation Time		
Translation Path		
Astronaut Positioning		
Tool Use		
Information Systems		
Development and Training		
Astronaut Work Environment		

Delivery	Suited Gateway	SPS Gateway
Number of Launches		
EVA Readiness		
EVA between crew visits		
Consumables/Logistics		
Cabin Air Loss/EVA		
Propellant (GN2)		
Oxygen		
Cooling Water		
Crew Sizing		
Tools		
Gateway Objectives		
New Skills		
New Technology		
Commercial		
International Partners		
Gateway Impact		
Interfaces		
Translation aids		
Work site		
External finish		
Acquisition		
Elements		
Launches		
Acquisition		
Training		
Estimated Cost		

Favored
Approximately Equal

Figure 3. Trade Findings favor SPS Gateway

Figure 4. Example of SPS Gateway.

spacecraft. The trade findings reveal that a SPS Gateway is the safer solution, weighs less, is more efficient, requires fewer consumables and one less launch, it fulfills the stated Gateway objectives and is less expensive. An example configuration is shown in figure 4. These findings remain unchanged regardless of the type of airlock used for suited EVA. Also, because SAFERs are required, nitrogen propellant is needed for both options. Furthermore, unlike suits, the SPS can be piloted or tele-operated allowing dangerous operations without risk to the crew. It is reusable and extensible to Mars transit, low gravity exploration (e.g., asteroids or Phobos), satellite servicing, and commercial space stations. It was observed that a SPS Gateway could be the beginning of new thinking for EVA; suits for the surface and small spacecraft for weightless operations (Figure 5). Although the SPS Gateway is the favored option, it is but a bold move. A more gradual "belt-and-suspenders" approach, though more costly would likely prove more acceptable.

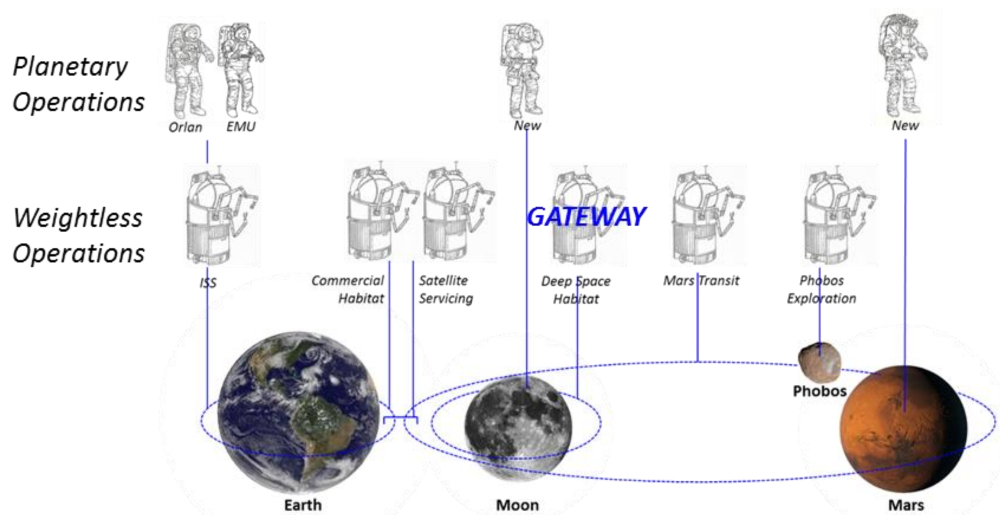

Figure 5. Case for Separate Planetary and Weightless EVA

IV. Trade Structure

A. Ground Rules and Assumptions

Because NASA intended the initial Gateway contracts to inspire innovative solutions, there are few formal requirements. Therefore, it was necessary to introduce ground rules and assumptions (Figure 6) as a foundation for this trade assessment. These were organized under three categories; Common, Suited EVA, and SPS EVA. Of critical significance is the Gateway cabin pressure and gas composition. It was assumed the Gateway atmosphere would be101.4 kPa (14.7 psi) comprised of approximately 20% oxygen and 80% nitrogen. This aligns with the draft

Common	Suited EVA (Continued)	Suited EVA (Continued)	SPS EVA (Continued)
Weightless operations	Gateway has a minimum of two suits plus spares	EVA tools, foot restraints, and tethers included	SPS is delivered Gateway elements or co-manifested with Orion
Gateway atmosphere is common with Orion , ISS, & Internationals	ISS pre-breathe protocol	No Suitlock or suitport	Gateway has a minimum of one SPS plus spares
EVA Activities include inspection, scheduled maintenance, unscheduled repair and possible one time connection of non-automated umbilicals	Suit resizing inventory at Gateway	Airlock includes pump to reclaim 90% atmosphere	SPS is sized for all astronauts
Gateway unable to retrieve EVA astronaut set free	Two SAFERs plus spares, servicing, and recharging systems	Airlock is a new build (STS and ISS airlocks used for reference)	SPS is berthed to vestibule attached to IDBM interface
Suited EVA	No new MMU	Robotic arm for astronaut positioning is an option	Vestibule delivered attached to Gateway element
Assume ISS EMU for Gateway space suit	LCVGs and MAGs for EVA crew	**SPS EVA**	No airlock
	Suits sized for two designated EVA crew per mission	SPS cabin atmosphere is same as Gateway	No robotic arm is required
	Gateway elements include EVA translation paths and worksite provisions	SPS can be piloted or tele-operated	

Figure 6. Ground Rules and Assumptions.

Interoperability Standard[8] and is the logical choice because it is common with the Orion crew transfer vehicle, ISS, Russian, Japanese and European spacecraft. Furthermore, under these conditions the air cooling of equipment is well understood as are the flammability and out-gassing properties of approved internal materials

B. Figures of Merit

Figures of merit (FOM) were selected to provide a comprehensive comparison for the Gateway. The eight FOMs (Figure 7) cover conventional measures but also include specific items such as Fulfilling Gateway Objectives. The FOMs represent an outline for the following material which is subdivided into particular areas of assessment under each heading. Generally, the supporting graphics show suited information on the left and SPS on the right.

Figure of Merit	Description
Intrinsic Safety Differences	*Concept unique characteristics are compared*
Mass	*Concept mass to enable Gateway EVA*
Efficiency	*Includes NASA Work Efficiency Index, information access, and other efficiency factors*
Delivery	*Launch and delivery of elements to Gateway orbit*
Consumables/Logistics	*Cabin atmosphere, oxygen, water, suit sizing, tools, and resupply items*
Fulfilling Gateway Objectives	*How well do the concepts comply with NASA's Gateway objectives*
Impact on Gateway Elements	*Gateway design and hardware features required to support each option*
Acquisition	*Government and commercial; Estimates on cost to implement Gateway EVA*

Figure 7. Figures of Merit used to compare EVA approaches.

V. Comparison Assessment

A. Intrinsic Safety Differences

1. Decompression Sickness (Bends)

All the atmosphere in the suit is at the same pressure, so glove pressure determines suit pressure. Hand use is essential to EVA and lower pressure reduces glove stiffness. Low pressure is also preferred because it minimizes

[8] International Environmental Control and Life Support System (ECLSS) Interoperability Standards (IECLSSIS), Draft C, February 2018

leakage, reduces joint torque, and improves mobility for translation and tool operation. For these reasons, the current ISS Extravehicular Mobility Unit (EMU) operates at 29.65 kPa (4.3 psi) which is slightly above the lowest pressure for respiration necessarily resulting in a pure oxygen breathing atmosphere. The transition between the higher pressure, mixed gas atmosphere of Gateway and the low pressure pure oxygen space suit presents a risk of getting decompression sickness or the "Bends." This is a major safety concern because according to the Undersea Hypobaric Medical Society, "the resulting clinical manifestations include joint pains (limb bends), cutaneous eruptions or rashes (skin bends), neurological dysfunction (peripheral or central nervous system bends), cardiorespiratory symptoms and pulmonary edema (chokes), shock and death."

To avoid the Bends, astronauts on Gateway need to pre-breathe pure oxygen for between 12.5 and 14 hours. In contrast, the SPS has the same cabin atmosphere as Gateway so there is no lengthy pre-breathing or risk of the Bends. Instead the SPS allows immediate access to space for long or short excursions by different astronauts (Figure 8).

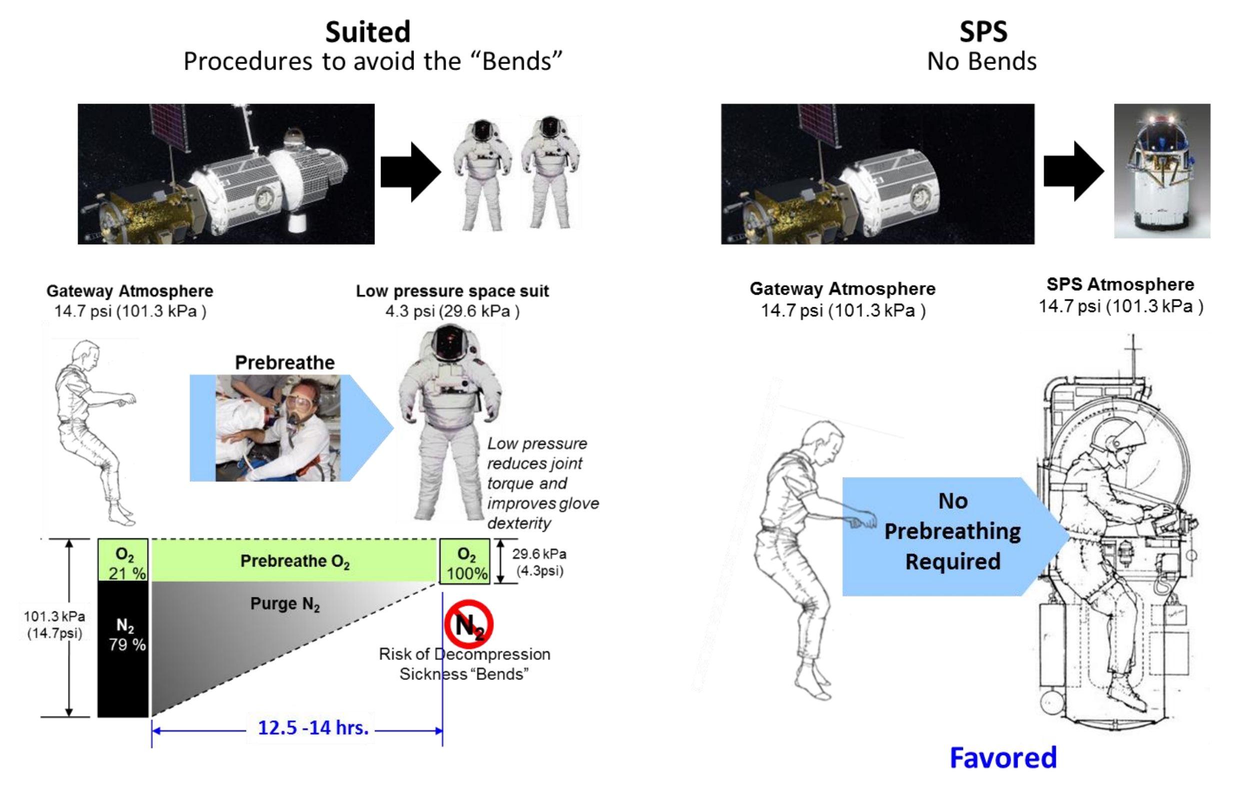

Figure 8. No risk of Decompression Sickness (Bends) with SPS.

2. Fire Risk

The pure oxygen environment in the suit represents an elevated fire hazard limiting the choice of internal materials and equipment selection. Figure 9 further describes the impact of increasing the percentage of oxygen in the atmosphere; there are fewer acceptable materials, fire suppression is ineffective, there is rapid fire propagation, and few materials self-extinguish. These limitations not only affect suits, but also the spacecraft systems that fill and store the high pressure tanks used in the backpack. There have been two notable incidents involving high pressure oxygen. The Apollo 1 fire that killed three astronauts is attributed to the 110.3 kPa (16 psia) oxygen environment and in 1980, a suit was destroyed and a technician severely burned during an unmanned test of the EMU. Perhaps the most far-reaching change of these events is the generation of an agency specification, NSS 1740.15, —Safety Standard for Oxygen and Oxygen Systems which covers materials selection, design, testing, and cleanliness for oxygen systems.[9]

[9] "U.S. Spacesuit Knowledge Capture," AIAA 2011-5199, C. Chullen, J. McMann, K. Dolan, R. Bitterly and C. Lewis

The SPS will have internal electronic equipment which does increase the potential of a fire. However, with same 20% oxygen, mixed gas atmosphere as Gateway, it represents well understood conditions and a lower fire hazard than space suits. Additional benefits include no high pressure oxygen system for filling backpack tanks, many more approved outfitting materials, and there is no additional cost for oxygen qualification of equipment.

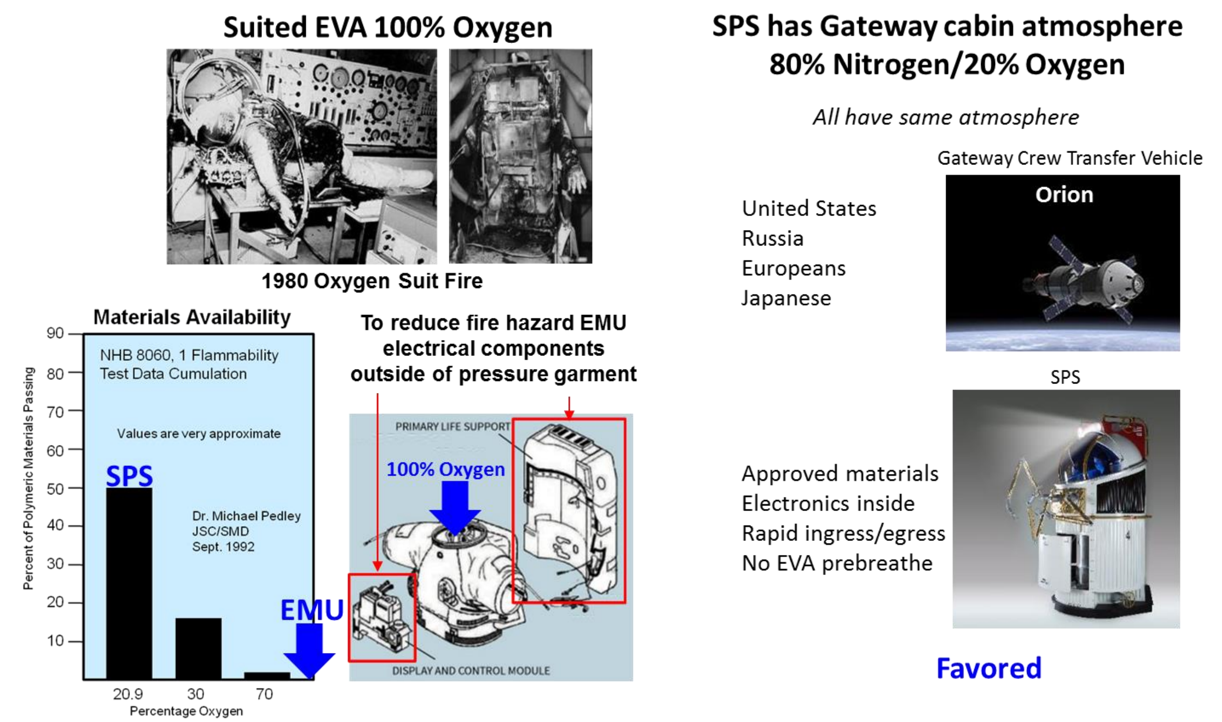

Figure 9. Higher fire risk with space suit pure oxygen atmosphere

3. Fire Control

Fire control refers to the ability to actually manage a fire that has started in the suit or the SPS. For suits, there is no recourse and this is why the design philosophy is aimed at eliminating ignition sources. Suit displays and controls are mounted externally and the backpack is physically separate from the pressure garment. For example, a $150 Polar heart rate monitor may require $200K (or more) of engineering testing, analysis and certification before it can be accepted for use inside the space suit.

The SPS includes a fire detection/suppression system and because the crew has the freedom to use their hands inside the vehicle, a portable fire extinguisher is provided.

4. Water Inside

As experienced on five EVAs, having free water inside the space suit is a very serious, potentially lethal situation[10]. Water is necessary to help cool the astronaut and normally is contained in plastic tubes woven into a form fitting "long-John" garment (Liquid Cooling Ventilation Garment LCVG)). Most notable was the spacewalk on July 16, 2013, in which water flooded the spacesuit helmet of Italian astronaut Luca Parmitano, forcing NASA to abort the spacewalk to get him to safety. Being in zero-g and not having hands inside makes it impossible to remedy the situation. In addition to nearly drowning, Luca's vision was obscured hampering his return to the airlock and the leak caused his communications cap to short out preventing him from reporting the emergency or hearing instructions.

The SPS does not use a liquid cooling garment so this source of water is not an issue. The air cooling system does use a water heat exchanger and in the event of leakage, the hands-in capability allows astronauts to contain the water

[10] NASA, "Significant Incidents and Close Calls in Human Spaceflight: EVA Operations," July 27, 2016

without lethal consequences (Figure 10). Since 2010, NASA reported 5 significant EVA water incidents and one visual impairment. These would not have been an issue with the SPS.

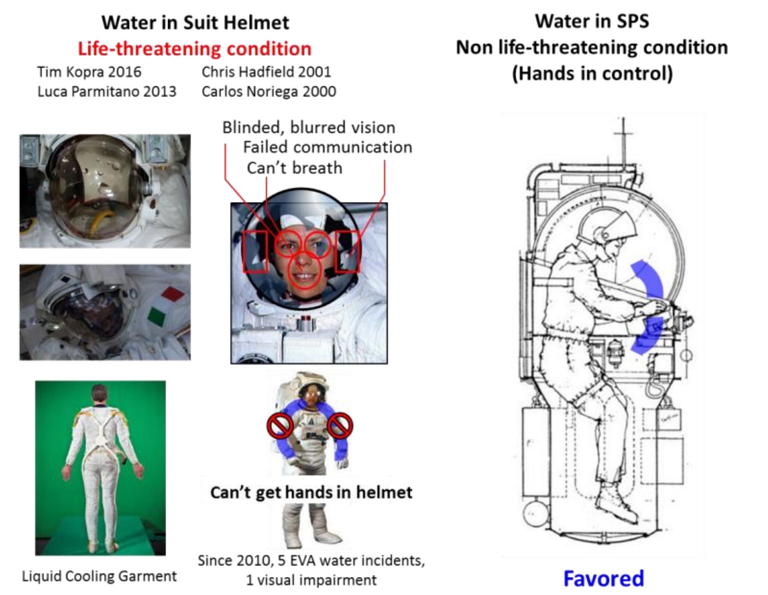

Figure 10. No life-threatening water problems for SPS.

5. *Radiation (Solar Proton Event)*

The radiation environment for Gateway astronauts is more severe than for the ISS crew. For Gateway there are two sources of radiation, Galactic Cosmic Rays (GCR), and Solar Particle Events (SPE). The risk associated with GCR radiation is cumulative and thus a function of exposure time. Currently there is no effective protection against CGRs. SPEs on the other hand, can be lethal, but because there is a warning time, the best approach is hold out in the Gateway shelter avoiding external operations during the events. For ISS, SPEs are not a big concern because it is protected by the Earth's geomagnetic shielding. For the cis-lunar environment, current space suits offer minimal to no radiation protection. The SPS however, provides multiple layers of protection not possible with space suits. These include a polyethylene outer or inner jacket and wearable radiation protection like ILC's concept in Figure 11 and a vest being developed by StemRad Ltd. an Israeli company.

6. *Out of Breathing Gas*

Both space suits and the SPS are equipped with an emergency breathing gas system. The difference is that for the space suit it is compressed oxygen and for the SPS it is compressed air. For this area of comparison there is no difference between the two options.

7. *Breathing gas leak*

If a leak is detected, then the astronaut opens the emergency gas supply to maintain internal pressure by "feeding the leak." Both space suits and the SPS use this procedure so there is no difference in response to a gas leak.

8. *Suit Trauma*

Suit induced trauma is a consequence of EVA that is often overlooked. In 2008, astronauts Carl Walz and Mike Gernhardt presented photographs of swelling, inflammation, and abrasions caused

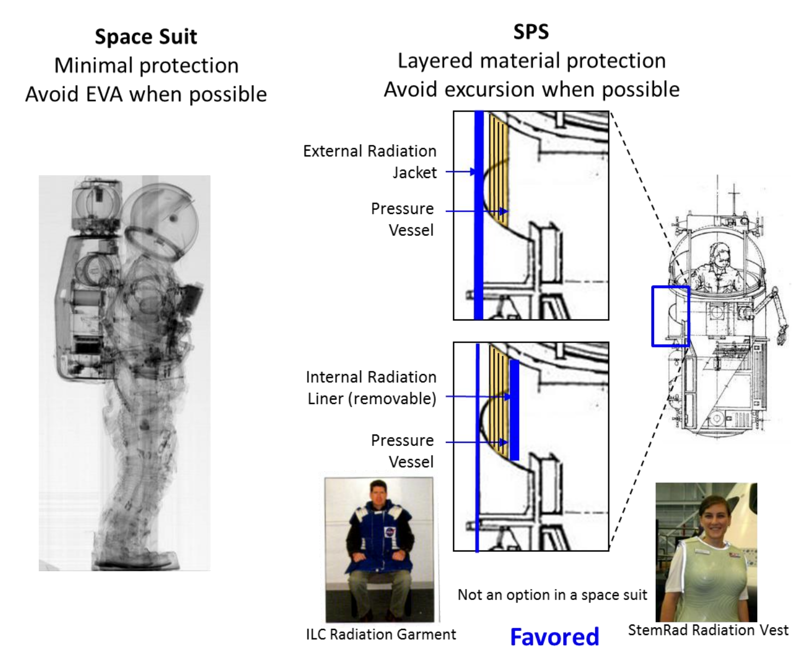

Figure 11. SPS provides layers of radiation protection.

by contact with the inside of the space suit (Figure 12).[11] They went on to report that the trauma can occur even with a minimal of EVA time. Although there is considerable effort placed on proper suit sizing, parts of the astronaut's

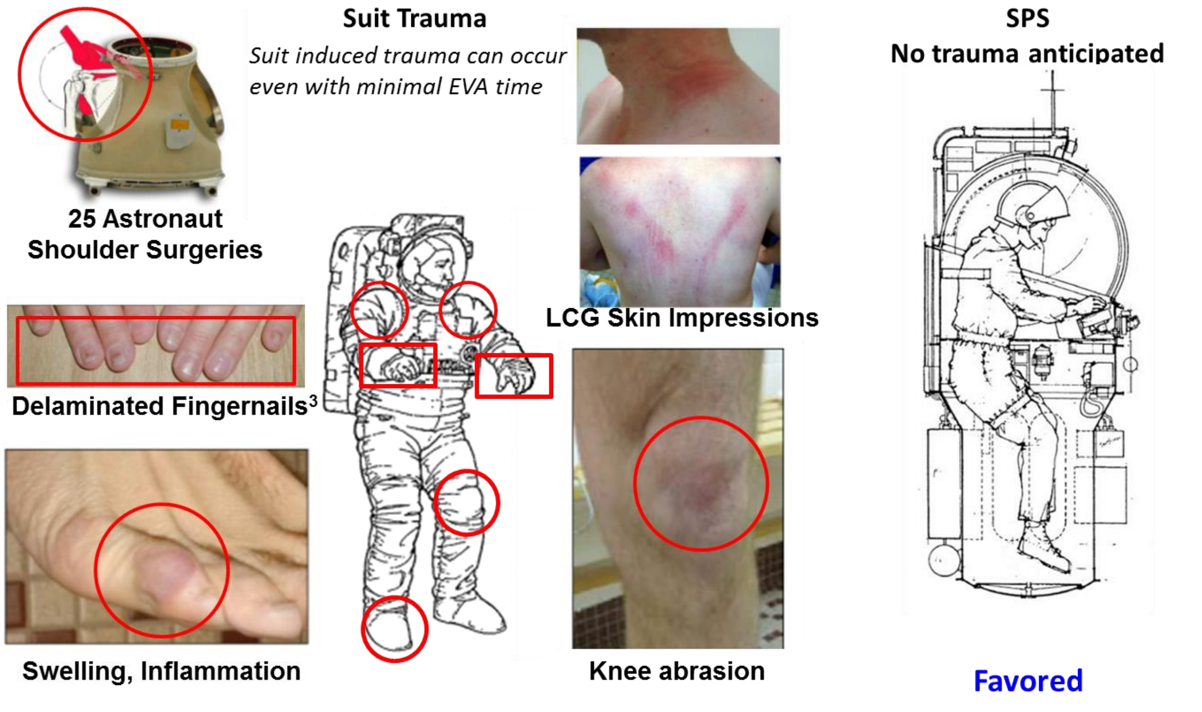

Figure 12. No suit induced trauma with SPS operations.

body press and rub against the rigid inner surface of the suit. This causes trauma at the contact points especially the hands, knees and toes. Hand trauma is a particular concern because grip and finger dexterity are essential for weightless translation, tool operation, and getting in and airlock operations. Probably most significant is the high occurrence of fingernail delamination[12] with EVA astronauts. This is important because favoring painful or sensitive hands may compromise safety and performance. Neutral buoyancy is the preferred method for suited EVA training and although the suit may be neutrally buoyant, the astronaut inside is still in earth's gravity. In an Aerospace Medicine report on injuries related to EVA suit design, it was reported that twenty three astronauts have had shoulder surgery, two on both shoulders.[13] SPS provides astronauts a shirt sleeve environment; therefore no suit induced trauma is anticipated.

9. Fatigue

Suited EVA is fatiguing. Astronauts, working against the internal pressure have to overcome joint and bending torque. The suit is designed with 14 layers which restrict mobility and when combined with the pressure, make using the gloves particularly difficult. On the earth, the large leg muscles react loads for most of our work; in a space suit, the small muscles in the arm have to react the mass of the suit, astronaut, SAFER, and tools which can easily exceed 227 kg (500 lb.) mass. Time in the suit is another factor contributing to fatigue. Because of the overhead time of getting to the worksite, EVAs are scheduled to accomplish as much as possible with the limits of the backpack. Therefore, they tend to be long, up to eight hours. Astronaut deconditioning plays a role on EVA gloves grip strength and fatigue. Applied Ergonomics reported that the space environment remarkably reduced strength and endurance of

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[11] Extravehicular Activity – Challenges in Planetary Exploration, Carl Walz / Mike Gernhardt, 27 February, 2008, Third Space Exploration Conference and Exhibit, Denver, CO

[12] Probability of Spacesuit-induced Fingernail Trauma is Associated with Hand Circumference, Opperman, R.A., et al, Aviation Space Environmental Medicine, Oct, 2010

[13] Shoulder Injuries in US Astronauts Related to EVA Suit Design, R. Scheuring, NASA Flight Surgeon, DO, MS, FAsMA, FAAFP, Aerospace Medical Association, May 11, 2012

astronauts.[14] Another study using the average task load index showed that the average for six areas of comparison was significantly increased for EVA as compared to hill runs (Figure 13).

Unlike space suits, SPS excursions are more like piloting a light aircraft. There is no suit-like fatigue and therefore task performance is not a function of physical conditioning. Duration is another important difference. Because there

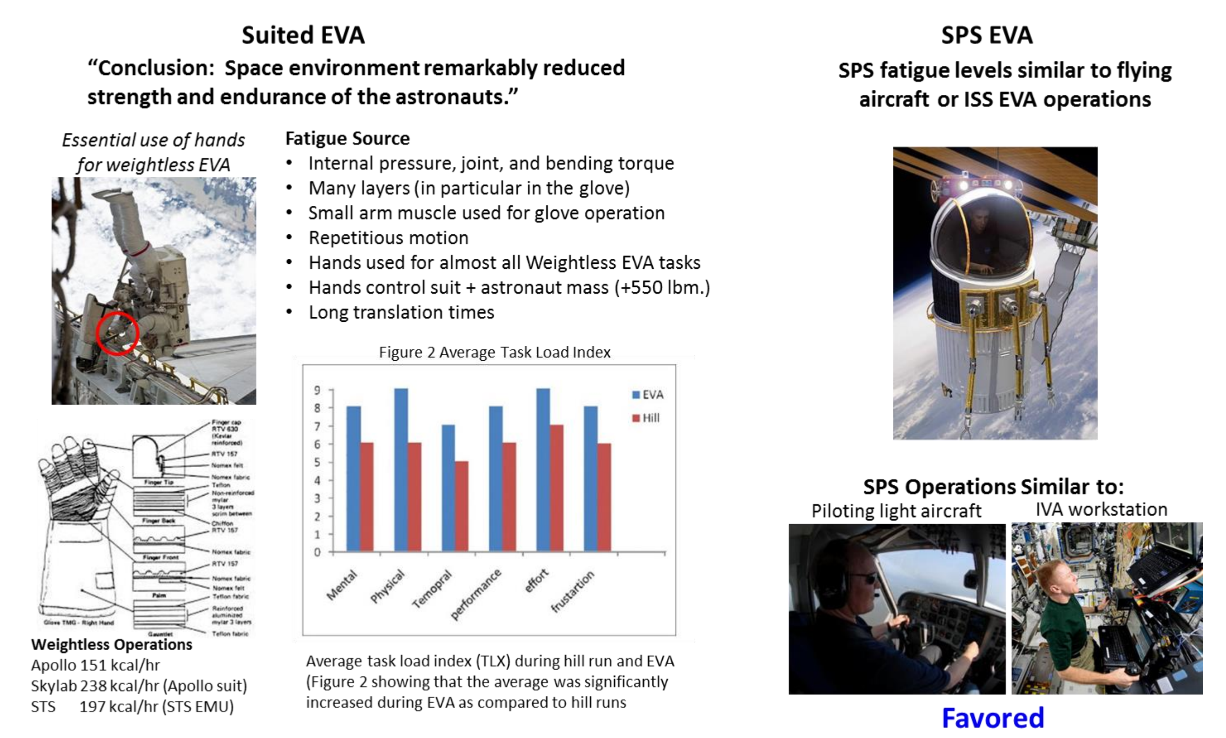


Figure 13. SPS eliminates suit fatigue.

is little overhead, no pre-breathing or airlock cycling, excursions can be short or long. Another advantage is all astronauts can fly the same vehicle, one right after the other. It is not possible for different astronauts to use the same suit for back-to-back EVAs.

10. Micrometeoroid Protection

In LEO, shielding is required to protect from micrometeoroid and orbital debris penetration. For high lunar orbit, there should be no debris but, without the earth's shielding, the Gateway has a greater micrometeoroid exposure. Space suit layering offers some protection, however the SPS includes a Whipple Bumper design just like ISS (Figure 14). Like the space suit, the SPS canopy has two polycarbonate layers and visors

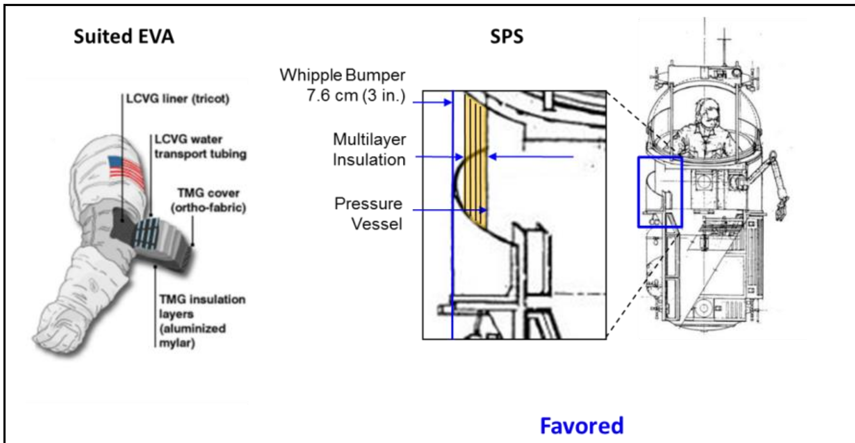


Figure 14. Whipple Bumper offers better micrometeoroid protection.

[14] Effects of EVA gloves on grip strength and fatigue under low temperature and pressure, Applied Ergonomics, Vol. 53, Part A, March 2016, pp 17-24

for protection while in operation and uses a deployable beta cloth cover when berthed. This concept offers greater protection for the crew.

11.Astronaut Set Free

It is frightening to think of an EVA astronaut being set free with no means of return. Gateway is not equipped to chase after an untether astronaut, so like ISS, Gateway astronauts will be wearing SAFERs to enable an emergency return. Several factors need to be considered for use of Gateway SAFERs. The current design fits snugly around and beneath the EMU backpack. NASA's new suit concepts are designed for rear entry which requires a new backpack and consequently the SAFER would need to be redesigned to fit the new backpack geometry. A factor contributing to the rear entry suit configuration is mating to either to a Suit Port or Suit Lock. Rear-entry introduces the potential of SAFER interference with the mating interface (Figure 15). Also, regarding acquisition, if the EMU is used and Gateway overlaps ISS, then at least two additional SAFERs plus parts would be required. Another consideration is that a fully functional SAFER is a necessary precondition for suited EVA. Therefore, Gateway needs to be equipped to assess SAFER flight readiness with the capability to top off or refill propellant because of leakage or use.

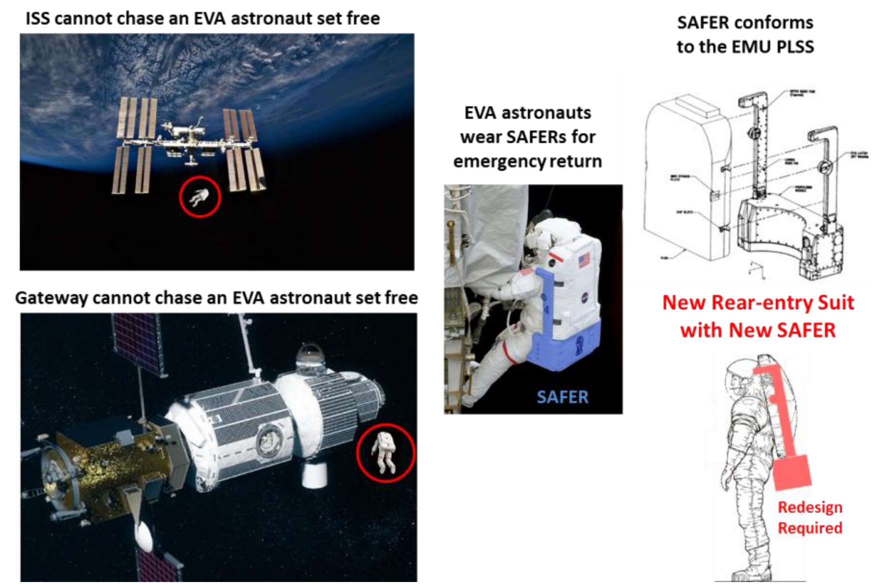


Figure 15. SAFER redesign required with rear entry space suit.

The SPS is designed for flight and for safety, it has the same level of redundancy as the human-rated MMU. The SPS also has an automated "return-to-base" function and in case of an incapacitated astronaut, tele-operation provides a safe return.

Considering that both the suited and SPS Gateway require propulsion systems for an astronaut set free, there is no safety discriminator.

12.Out of Propellant

Both the SAFER and SPS use compressed nitrogen for propellant. The SAFER propulsion system is intended for emergency return while the SPS is designed for both nominal and emergency operations. Comparing emergency operations, if the SAFER runs out of propellant, there is no recourse. However, if the SPS is out of propellant, it is designed to use the compressed emergency breathing air as propellant. Hopefully, this situation never happens, but with its redundant propellant source, the SPS is favored.

B. Mass

Mass for the Gateway trade includes all the hardware required to conduct suited or SPS EVAs (Figure 16). No airlock is required for the SPS, however concepts for a suited Gateway airlocks vary from contractor to contractor, so flown airlocks were used as reference for mass comparison. This is reasonable because these airlocks cover the extremes with the smallest being a Space Shuttle internal airlock and largest, the ISS Quest combined equipment lock and crewlock.

1. Shuttle Airlock/One SPS

For a comparison of minimum mass, a Gateway with a Shuttle airlock is compared to having one SPS with a berthing vestibule. The SPS Gateway is 582 kg (1282 lb.) lighter than the suited solution (Figure 17). It is worth noting that the suited Gateway also includes two suits, two SAFERS, a pump, cooling garments, tools, translation and worksite aids and a sizing inventory to accommodate visiting crew.

2. ISS Airlock/Two SPSs

Comparing the ISS Quest airlock to two SPSs is a comparison of maximums. The NASA Gateway and some contractor concepts depict a Quest-type of airlock. It is ideal because there is a larger dedicated volume for suit stowage, don/doff, and servicing attached to separate small volume airlock. Compared to the Quest airlock, the Gateway with two SPSs is 5437 kg (11,788 lb.) lighter.

Gateway is even more sensitive to mass than ISS because of the additional energy required to transport elements to cis-lunar space. With all the equipment required to support suited EVA, a suited Gateway will be the heavier option.

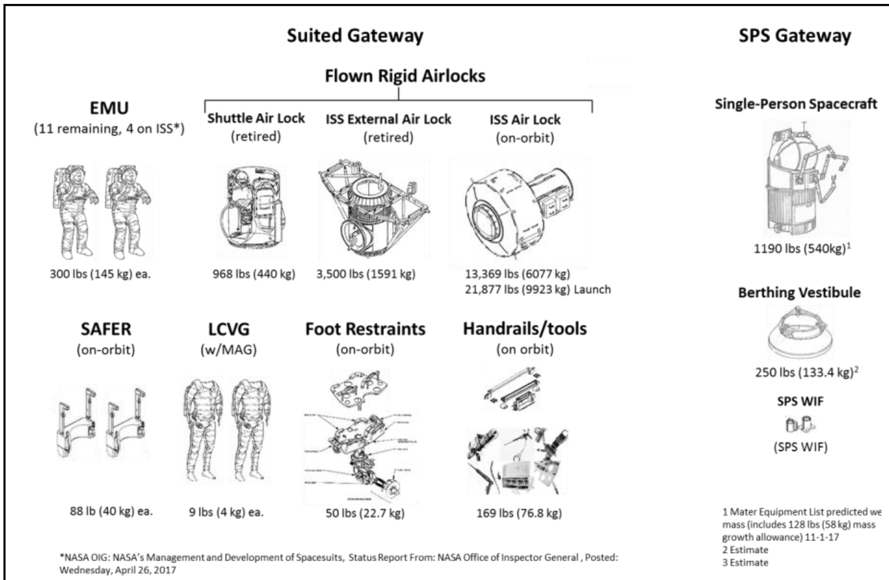


Figure 16. Space Suit and SPS Mass

C. Efficiency

1. Work Efficiency Index

In addition to pre-breathing, there are suit related tasks that require crew time. The Work Efficiency Index (WEI) is a common measure of EVA efficiency that shows a ratio of task time to overhead time (Figure 18). For example, a 6 hour EVA with 3.0 hrs. overhead has a WEI of 2.0. Apollo astronauts had a WEI of 2.0; however for ISS it is between 0.39 and 0.43. Suit preparation, pre-breathing and airlock operations all contribute to this low number. The SPS is a vehicle with minimal overhead. Similar to aircraft, it is assumed 20 minutes of crew time would be spent on pre and post flight vehicle activities. With a 4 hour excursion the SPS has a WEI of 12.0. For a 7 hr. excursion, the SPS WEI is 21 which is over 40 times more efficient than suited EVA. This disparity is no surprise to NASA. R. Fullerton states

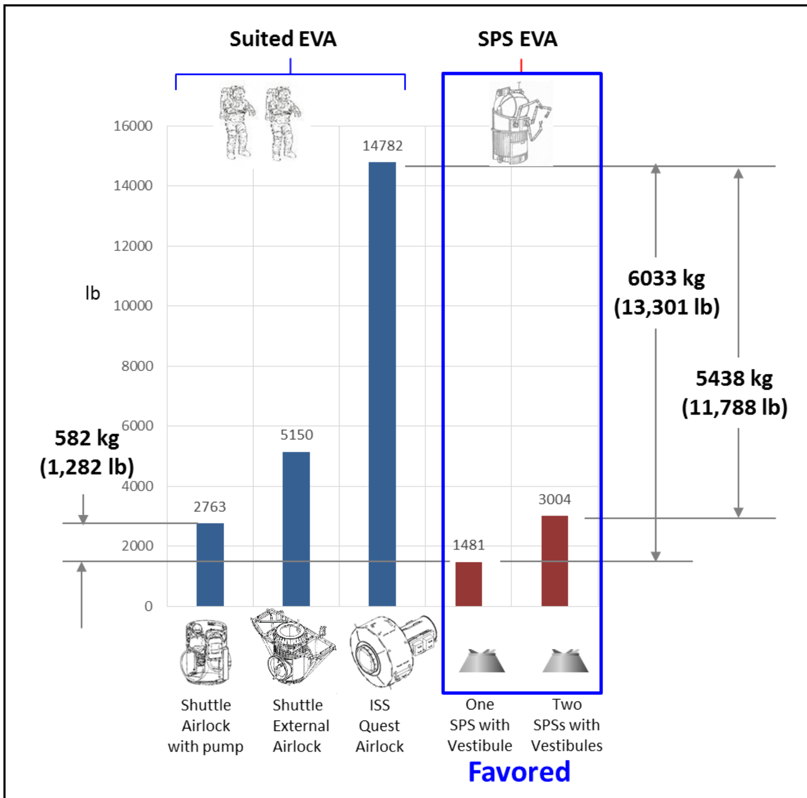


Figure 17. SPS is the lower mass option.

that historically, less than 20 percent of crew time related to extravehicular activity (EVA) is spent on productive external work.[15]

2. Translation Time

The SPS has integral propulsion and therefore can fly directly to the work site. Typically, a low energy trajectory is used to get to and from the work site, but for urgent situations, forced motion shortens the transit time at the expense of using additional propellant. The SPS propulsion system is the same as the flight-proven Manned Maneuvering Unit (MMU) (Figure 19). SPS nitrogen tanks are larger to provide extended range, but have the same pressure as the MMU. In comparison, the translation time for EVA astronauts is affected by the suit configuration, tools carried, moving tethers and the pathway or landscape to the work site. Times recorded from an ISS Increment 9 task include: 9 minutes from hatch to Strella, 15 minutes to PMA1, 5 minutes to SO and 14 minutes for tool configuration and translation to the work site[16]. Some Gateway configurations include a robotic arm. For ISS, the Space Station Robotic Manipulator System (SSRMS) provides another method of translation that includes a mobile foot restraint for the EVA crew. It is slow, 15 cm/sec (6 in/sec) and because the EVA crew member does not have controls, it cannot be operated like a cherry picker on Earth[17]. Another crew member inside is required to operate the arm. For extended reach the SSRMS is attached to a mobile transporter that moves along the ISS truss segments. Because the transporter creeps along at 2.5 cm/sec (1 in/sec) it is used for cargo and not crew

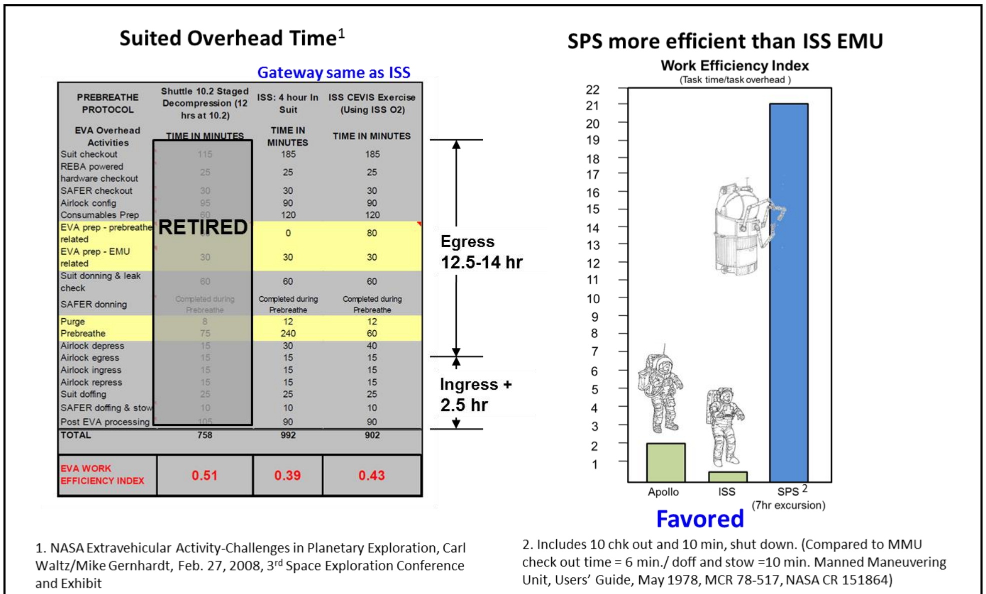


Figure 18. SPS operations are more efficient than suited EVA.

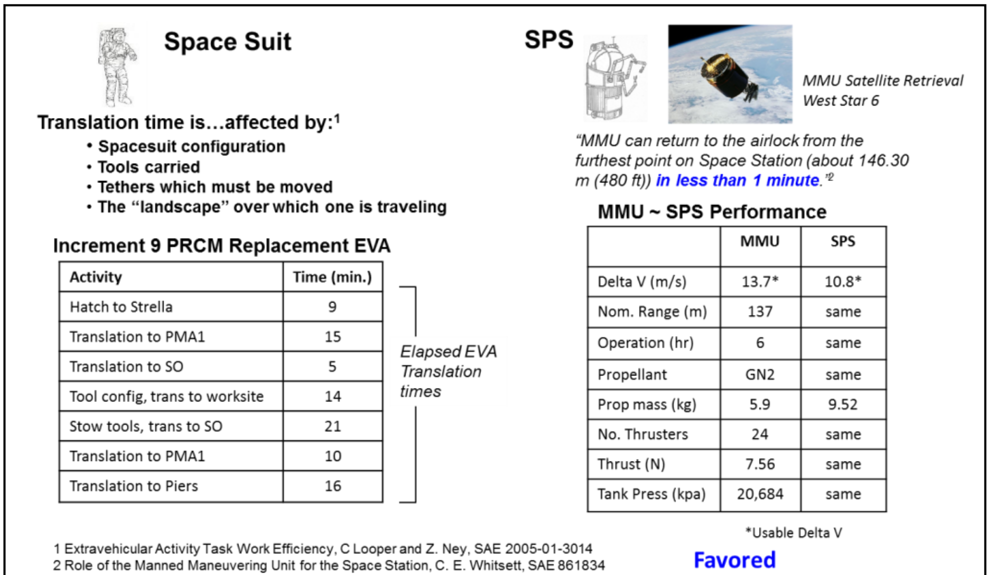


Figure 19. SPS quicker translation means more time on the job.

[15] "Advanced EVA Roadmaps and Requirements," ICES01-2200, R. K. Fullerton, NASA, JSC
[16] Extravehicular Activity Task Work Efficiency, C Looper and Z. Ney, SAE 2005-01-3014
[17] International Space Station, Robotics Group, Robotics Book, JSC 48540

translation. Consumable backpack resources limit EVA time therefore it is critical to devote these precious resources to the task rather than translating back and forth.

3. Translation Path

Translation paths are essential for suited astronauts to get from the airlock to the worksite and back. Because EVA pathways have access envelopes with structural requirements for handrails and tethers, they are usually predetermined routes leading to locations equipped for EVA servicing (Figure 20). Translation is all by hand. Small arm muscles must react the mass of the suit, SAFER, tools and astronaut totaling over 227 kg (500 lbs.) Managing this large mass usually means slow and deliberate action for both going and returning. In contrast, the SPS does not need translation paths because the astronaut can fly directly to the work site. Like EVA, serviceable sites will designate contact hazards and be equipped a reaction anchor point the SPS equivalent of Work Site Interface (WIF). For Gateway, the SPS is favored because it provides a more efficient means of translation.

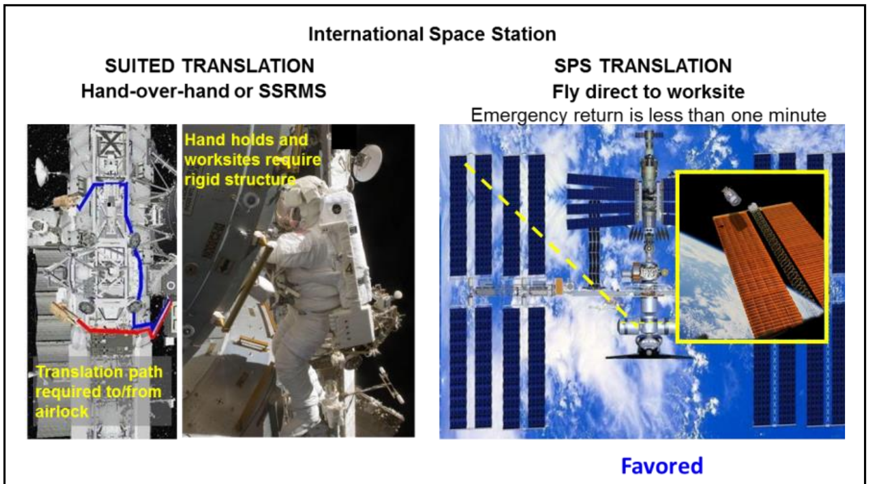


Figure 20. No translation paths or hardware required for SPS.

4. Astronaut Positioning

One challenge for weightless EVA, is positioning foot restraints so that astronauts can reach and see the work area (Figures 21 and 23). It is important that the restraint clocking, angle and distance from the work area are adjusted to accommodate individual astronaut anthropometry. Foot restraints are attached to rigid structure or on the end of a

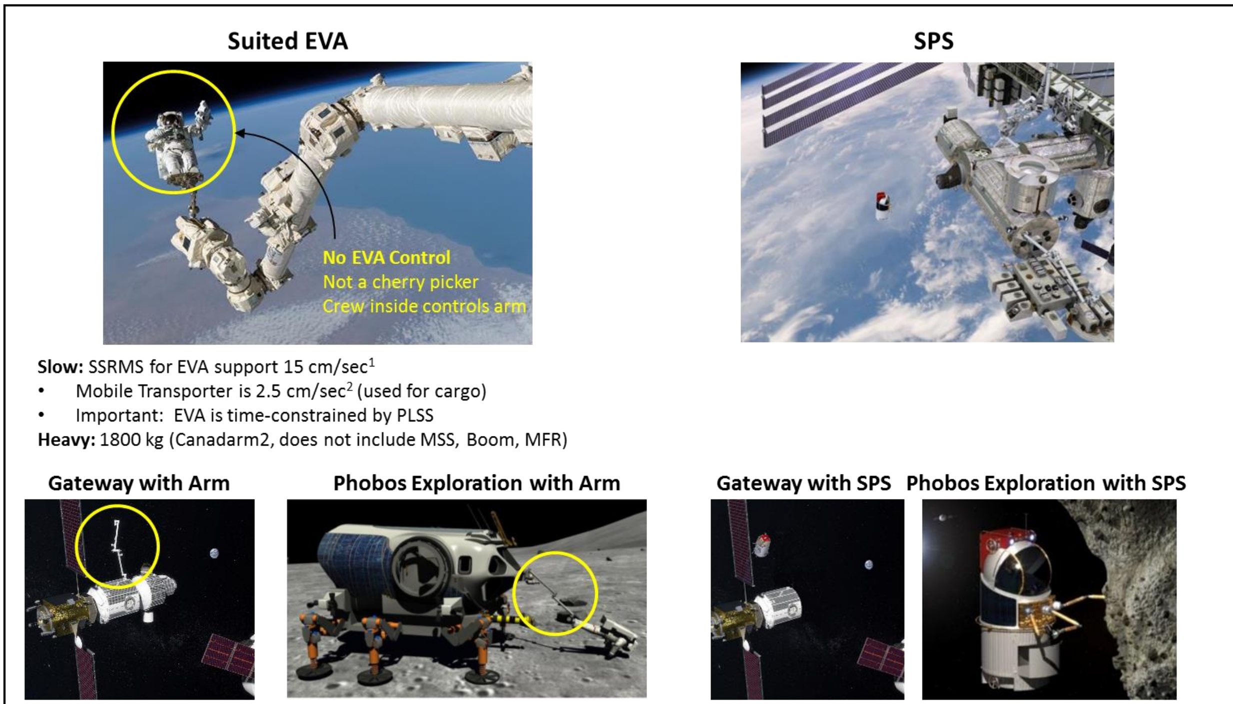


Figure 21. Both suited and SPS astronauts have methods of positioning astronauts for work.

robot arm, but the objective is to position the crew member so that the task is within the prime work envelope. For similar work, the SPS does not require pre-positioned foot restraints or a robotic arm. It flies to the site then, depending on the task, is stabilized using prepositioned anchors, propulsive attitude hold or manipulators grasping adjacent structure. This approach eliminates time and effort of translating with and setting up foot restraints while enabling work in areas that are either not accessible by suited astronauts or lack provisions for restraint.

Like the MMU, the SPS is positioned by using its thrusters. SPS astronauts not only have a wide field of view but their vision is augmented by external cameras on the vehicle and on the manipulators. When needed there are several methods of reacting manipulator tool loads. A stabilizing manipulator arm attached to a preposition anchor point, zero-torque tools, and the SPS propulsion system.

In comparing the two approaches, it was determined that, although different, both provide a means of astronaut positioning and therefore one was not favored over the other.

5. Tool Use

EVA astronauts do not use gloves to turn nuts or bolts. They use tools. This portion of the trade examined which approach was more efficient for using the tools at the job site (Figure 22).

Compared to a mechanical connection, an EVA glove is not the ideal interface for tool handling. It relies on continuous grasping through a many layered glove that is pressurized. Furthermore, restrained by a fixed foot restraint means the work area may not be within the line of sight thus interfering with accurate positioning and use of the tool. Astronauts are pretty good at getting the job done, but there is a higher potential for misalignment and error.

Figure 23 shows the SPS using a robotic arm to position a tool

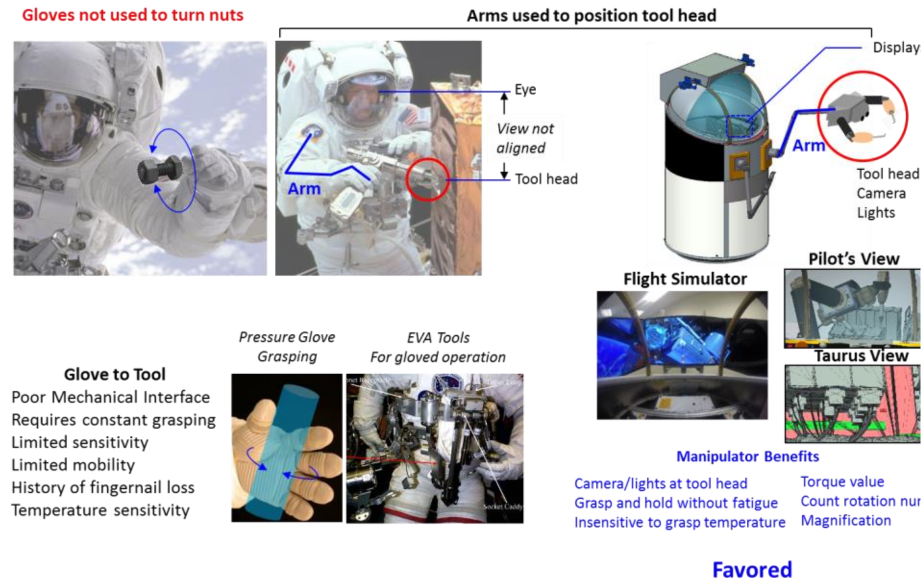


Figure 22. SPS provides more efficient tool use.

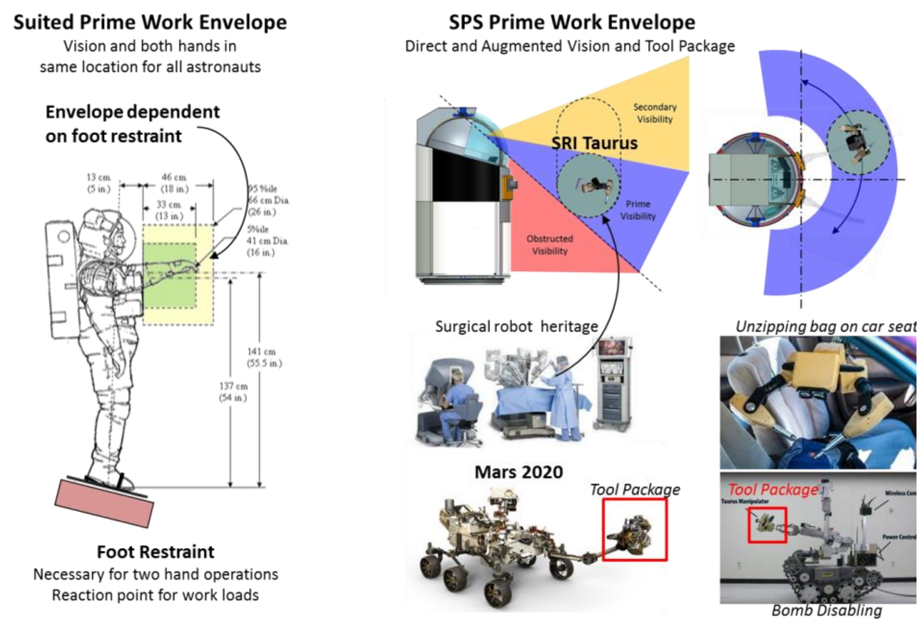


Figure 23. SPS has enlarged work envelope and includes tool head vision system.

package. This represents a unique advantage over the space suits because rather than having to position the body for reach and visibility, the robotic arm positions a tool package. This can get into places inaccessible by suited astronauts bringing lights and cameras for display inside the SPS. Similar to the Mars 2020 rover, the SPS is equipped with a tool package called Taurus created by SRI, the same organization that developed the first surgical robots. It only weighs 6.8 kg (15 lb.) and has a small porthole entry of 35.6 cm x 13.2 cm (14 in. x 5.2 in.). Furthermore, Gateway EVA is best characterized by servicing and repair activity; tasks that are ideally suited for SPS/Taurus operations.

6. Information System

EVA for Gateway and beyond will necessarily be more autonomous. The purpose of this part of the trade is to determine which approach offers the more efficient information system for future EVA systems.

With docking ports used to connect elements, there will be little to no ISS-type assembly; instead EVA tasks will focus on maintenance and repair. Events will be less scripted for visiting crews and therefore astronauts need to have real time, guiding, information. For this, the SPS provides an information system with controls and multiple flat panel color monitors for displaying camera views, checklists, schematics, and SPS health. This capability is not an option when the communication to Earth prohibits timely discussions with ground resources. Having "YouTube" like access to procedures and videos provides an efficient means for astronauts to accomplish never before seen tasks. In space suits, the hands are the manipulators so grasping precludes simultaneous access to controls. For SPS, manipulators can grasp and hold thus freeing the hands for other operations. The EMU displays and controls are mounted externally on the chest and are operated with the pressurized glove (Figure 24). Some controls are out of view which means astronauts wear a mirror attached to the sleeve to confirm settings. For displays, the EMU uses a 20 character LCD providing limited alpha-numeric information. There have been concepts for improved suit displays and controls, but none compare with the hands-in, cockpit-type operations of a spacecraft. The SPS is favored for information systems.

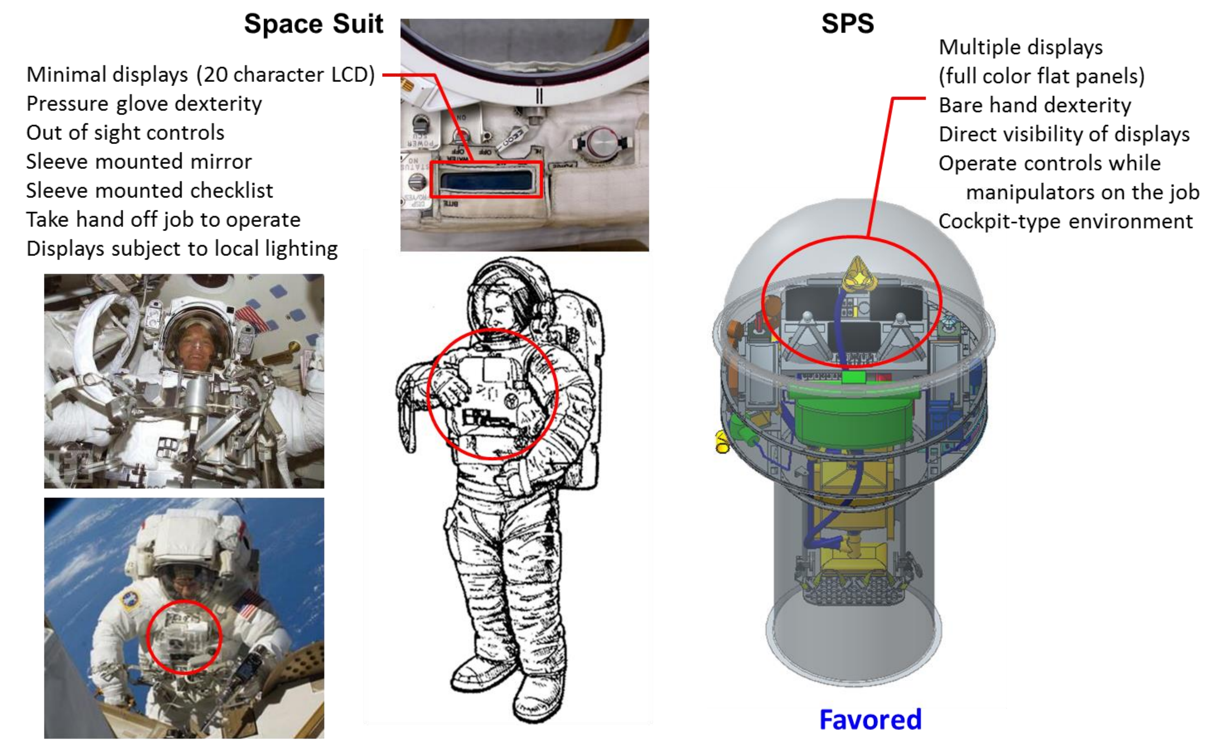


Figure 24. SPS provides the information system necessary for Gateway EVA.

7. Development and Training

Possibly one of the most significant differences with the biggest potential cost savings is in development and training. For weightless development, space suits use neutral buoyancy, parabolic aircraft, and a flat floor. All require special conditions (e.g. water facility, aircraft, and precision flat floor) and are operated by specially trained personnel. Neutral buoyancy is used most often with NASA training done in the Neutral Buoyancy Laboratory (NBL). The NBL is the largest indoor water pool in the world and is supported by more than 200 employees, including 60 core divers[18]. A training session consists of two astronauts in suits weighted for neutral buoyancy along with safety divers, utility divers and control room personnel. For safety, personnel and equipment maintain current certification requirements and the facility has a hyperbaric chamber for treating the bends. The current contract to support the facility has a three-year base period is valued at $67.6 million with two one-year options totaling $52.3 million.[19] For Gateway, new flight-like neutral buoyancy hardware would need to be constructed and if new suits are part of the design, then additional neutral buoyancy training suits would be required.

In contrast, the SPS approach uses proven aircraft-like simulation both for agile, low-cost development of the vehicle and for follow-on training (Figure 25). Early development is done by engineers in conventional office environment, then as control and display concepts mature, a SPS shell will be configured for operations assessment. This includes a flight-like mockup with immersive visualization. Like with aircraft, the operator inputs are linked to algorithms for accurate flight control around Gateway, asteroids or other spacecraft. This approach is low cost because it does not require special facilities or unique safety certifications. It allows anytime access and emergency procedures can be performed without risk to hardware or personnel. Another important feature is that it is possible to maintain proficiency on-orbit with "laptop" simulations.

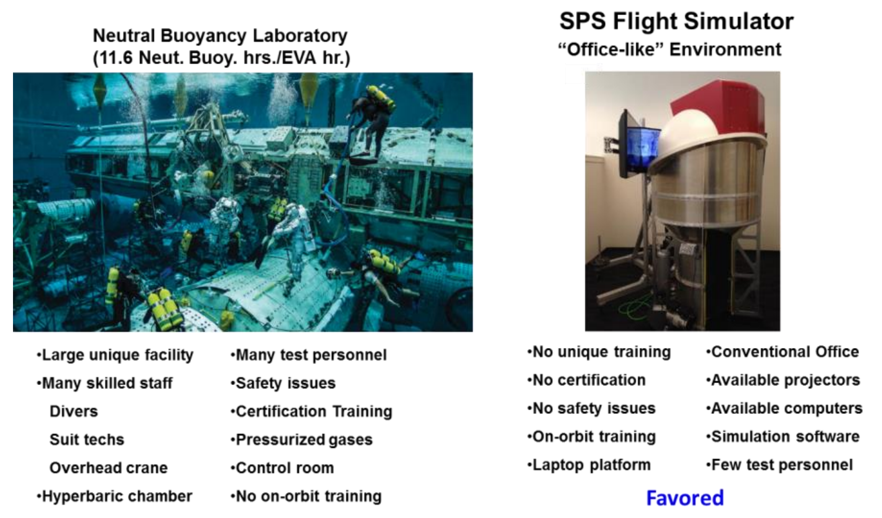


Figure 25. Low cost, efficient SPS simulator for development and training.

8. Astronaut Work Environment

Working in a space suit is physically demanding and typically EVAs 7.5 hours long. This is why the EMU is equipped with drinking water to quench thirst and make up for sweating (Figure 26). Because there is no way to bring the arms inside, astronauts move their head to access a helmet mounted drink bag. A food stick was

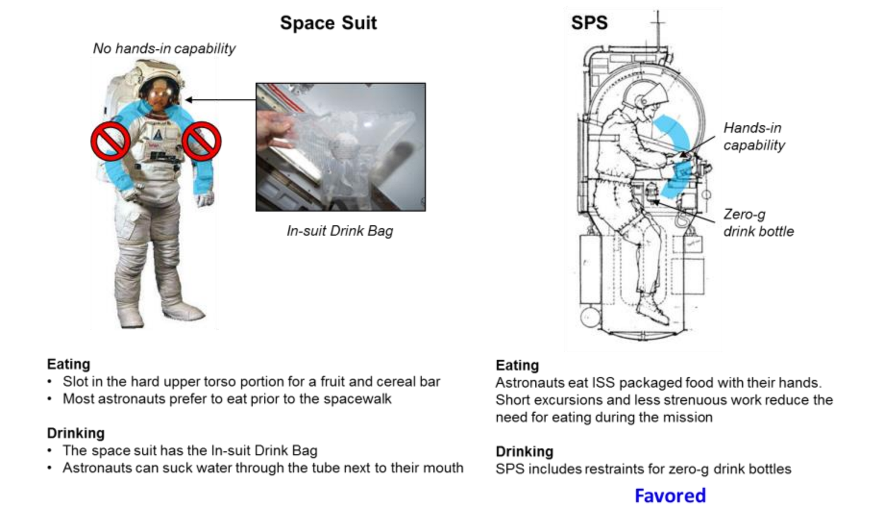


Figure 26. SPS provides improved hands-in work environment.

[18] "Behind the Scenes Training," NASA. May 30, 2003, Retrieved March 22, 2011

[19] CONTRACT RELEASE: C10-044, NASA Awards Neutral Buoyancy Laboratory, Space Vehicle Mockup Facility Support Contract

provided but most astronauts prefer to eat before the EVA and not use the food stick. The in-suit drink bags hold 1.9 liters of water which is consumed by sucking on a straw-like tube. With hands-in capability, the SPS provides easy access to conventional weightless drink containers and food if desired. However, because the work is less demanding and short excursions are likely, astronauts may avoid taking food or drink to eliminate a potential "spill" or particulate contamination.

9. Number of Launches

NASA's reference Gateway requires four SLS launches with one delivery dedicated to an airlock module. If the Gateway airlock is modeled after the ISS Quest with a combined equipment and crewlock then it will require a separate launch. At the date of this writing, contractors show different Gateway configurations, but most include a separate airlock module for suited EVA. Launching an airlock module adds significant cost and risk to the program.

The SPS on the other hand, does not require an airlock. Instead, the SPS is co-manifested on the logistics delivery with the berthing vestibule attached to an earlier element delivery (Figure 27).

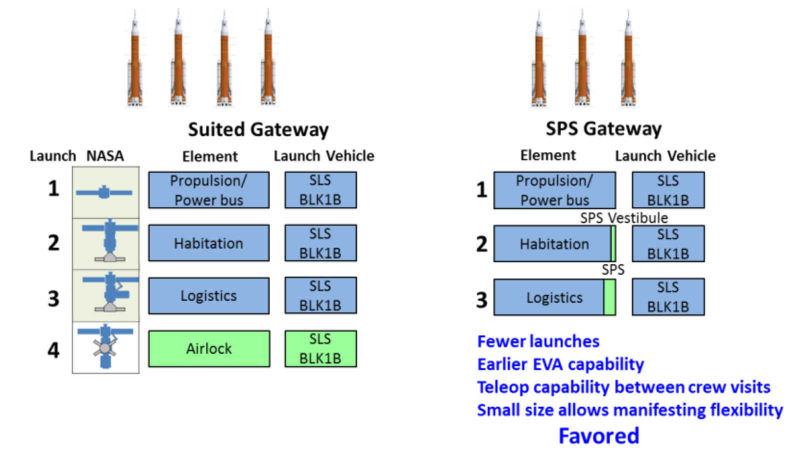


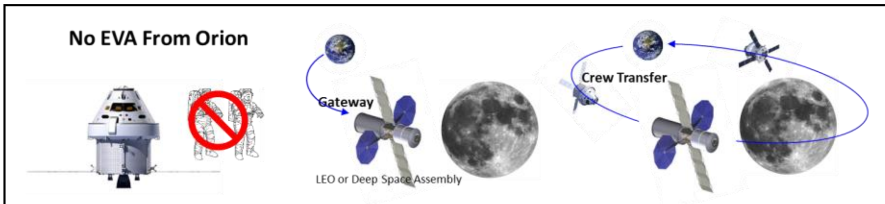
Figure 27. No airlock reduces the number of delivery flights.

10. EVA Readiness

Because the Orion is not intended for EVA, a suited Gateway would only be able to conduct an EVA when the airlock was present. For NASA's Gateway this would be after the fourth delivery, possibly four years after the first element. This precludes fixing problems that might occurs during the buildup. With the SPS, EVA would be possible on the second or third delivery flight.

11. EVA Between Crew Visits

Because the Gateway is crew tended, it will be unoccupied for extended periods. It is possible that problems between visits require attention before the crew arrives. In the tele-operated mode, the SPS is able to inspect and possibly repair damage (Figure 28). With a suited Gateway, this work would have to wait until the crew arrived.



Option	Suited Gateway	SPS Gateway
Assembly/ Emplacement	• EVA from Gateway (Orion not intended for EVA) • Suits, airlock and EVA provisions required prior to crew arrival (inventory for crew sizing) • EVA resupply separate delivery module (not Orion)	• SPS teleop for fly around inspection before crew visit
Crew Tended Operations	• Uncertainty of suit readiness between visits • Different crew requires suit resizing • Gateway unoccupied (suit soft goods servicing schedule)	• Readiness confirmed before crew visit • Tele-op between crew visits

Figure 28. SPS provide tele-operated EVA between crew visits.

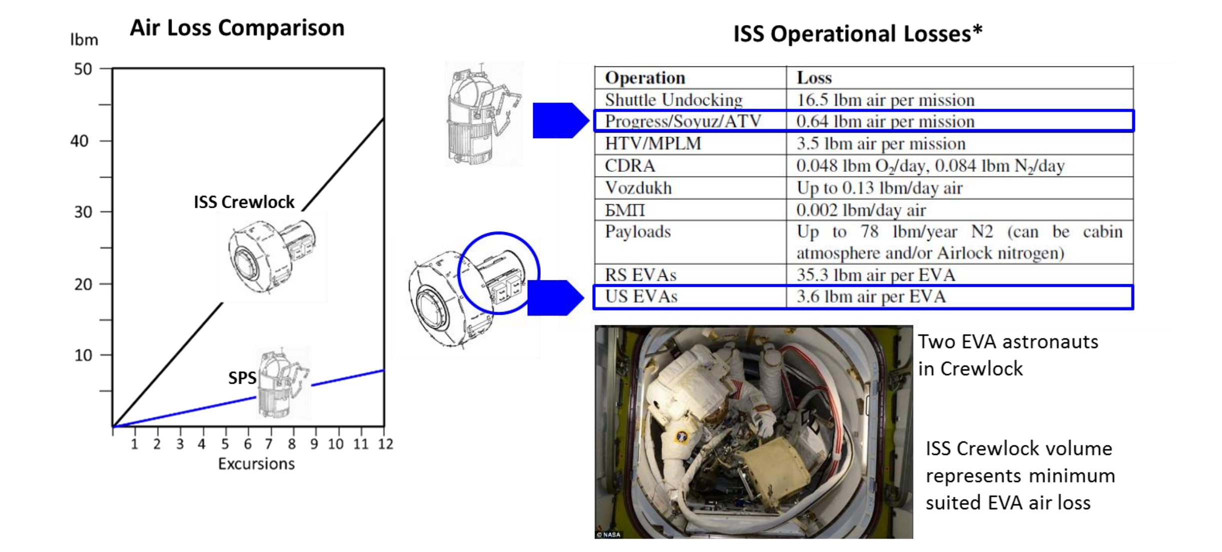
D. Consumables/Logistics

1. Cabin Air Loss/EVA

For all manned spacecraft, cabin air is a precious commodity; especially far away from earth in lunar orbit. Modules are designed for a minimum of leakage and the ECLSS is intended to reclaim most of the cabin air. To further minimize losses, it is assumed a small volume airlock similar to the ISS Crewlock would be equipped with a pump.

Even with this small volume, ISS documentation reports that after reclaiming 90% of the airlock gas, 1.6 kg (3.6 lb.) of cabin air is lost per EVA.[20]

The SPS does not need an airlock or pump, but does require venting the berthing vestibule before separation. The vestibule volume is expected to be similar to the Progress/Soyuz connection where the air loss is 0.3 kg (0.64 lb.) This means that the unrecoverable air loss for suited EVA is 5.5 more than the SPS (Figure 29); therefore, the SPS is favored.



Operation	Loss
Shuttle Undocking	16.5 lbm air per mission
Progress/Soyuz/ATV	0.64 lbm air per mission
HTV/MPLM	3.5 lbm air per mission
CDRA	0.048 lbm O_2/day, 0.084 lbm N_2/day
Vozdukh	Up to 0.13 lbm/day air
БМП	0.002 lbm/day air
Payloads	Up to 78 lbm/year N2 (can be cabin atmosphere and/or Airlock nitrogen)
RS EVAs	35.3 lbm air per EVA
US EVAs	3.6 lbm air per EVA

*Trending of Overboard Leakage of ISS Cabin Atmosphere, R. Schaezler, A Cook, D. Leonard, A. Ghariani, AIAA 2011-5149

Figure 29. Suited EVA loses 5 times the cabin air per excursion.

2. Propellant

This aspect of the trade compares the GN2 propellant for SAFER and the SPS, not the Gateway propulsion system. Obviously, the usage is different, SAFER is an emergency system while the SPS uses propellant on every excursion. Based on MMU performance, a 91.4 m (300 ft.) excursion carrying 113.4 kg (250 lbs.) cargo six excursions a year would use 18.3 kg (40.32 lb.) of GN2. One of the ISS Nitrogen Oxygen Recharge System (NORS) tanks holds 27.2 kg (60 lbs.) which would provide the annual supply with margin. Because SAFER needs to be operational for every EVA but may never be used, it is not clear what kind of system would be used for makeup gas or a recharge. If the SAFER were used, it would need to be recharged or Gateway would need to have another SAFER on board before another EVA could be conducted. In terms of propellant usage, suited EVA is favored because less propellant is required.

3. Oxygen

The big difference in oxygen consumption is the pre-breathing required before a suited EVA. Based on the oxygen used for ISS EVAs, there is up to 11 kg (24 lbs.) more oxygen required per excursion than with the SPS. Assuming six EVAs a year, two suited crew would consume 68 kg (150 lb.) oxygen compared to only 1.8 kg (4.14 lb.) for the SPS. Also contributing to this difference is that unlike suited EVA, the SPS has an Air Management System that reclaims oxygen. With regard to oxygen consumption, the SPS is favored.

4. Cooling Water

Both options use water for cooling. Space suits connect a liquid cooling garment and heat exchanger to a sublimator while the SPS uses air cooling and a state-of-the-art water membrane evaporator. It was assumed that an average of 4 kg (9 lb.) water would be used for two suited crew on each EVA. Of course, physical exertion and

[20] Trending of Overboard Leakage of ISS Cabin Atmosphere, R. Schaezler, A Cook, D. Leonard, A. Ghariani, AIAA 2011-5149

duration are factors, but this is an average considering the range from 3.4 to 5.4 kg (7.6 to 11.8 lb.). With 2.3 kg (5 lb.) for each excursion, the SPS is the favored option.

As shown in Figure 30 the SPS Gateway uses 66.9 kg (147 lb.) less gas and liquid consumables per year. Because of the uncertainty, this difference does not include any GN2 for suited EVA.

5. *Crew Sizing*

Space suits must be configured to fit each EVA astronaut. With approximately 41.2 cm (16.2 in.) difference in stature between the 1st percentile female 1.48 m (58.5 in.) and 99th percentile male 1.93 m (76 in.), different limb lengths, body dimensions and crew preferences fitting suits is challenging on the ground, let alone in zero-g (Figure 31). To give a sense of the scale of spacesuit support, the current EVA contractor processes more than 500 components for the space suits and 250 tools used during planned Shuttle/ISS EVAs.[21] For the suit pressure retention system alone there are 84 parts not including the gloves or backpack. The Shuttle provided an excellent method of transporting EVA trained astronauts with their tailored space suits to and from ISS. Because suits take up a lot of volume and weigh 136 kg (300 lbs.) it is unreasonable to assume visiting crews to transport their own suits. Instead, like ISS, an inventory of parts will be available for crew to resize and check out their suits. For ISS there are 106 parts.

The SPS is designed to accommodate all crew with adjustable restraints that position the body for

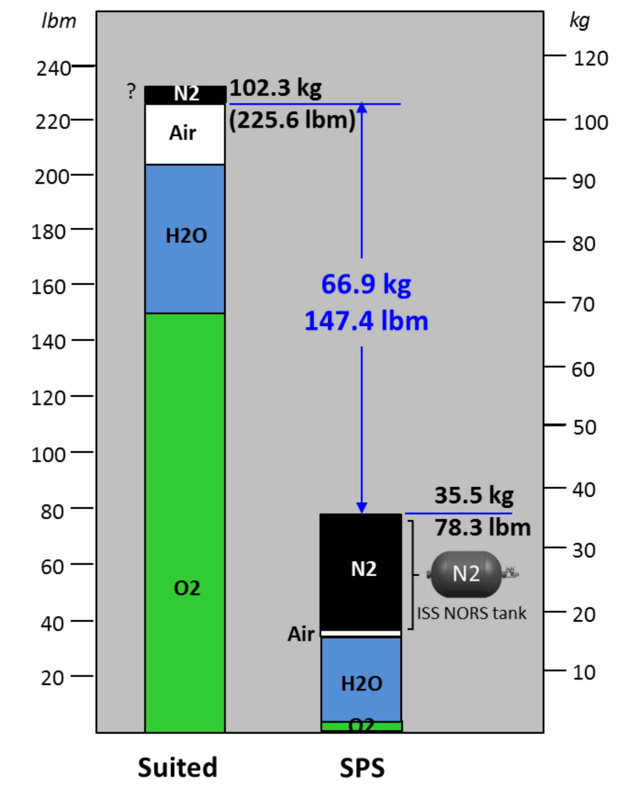
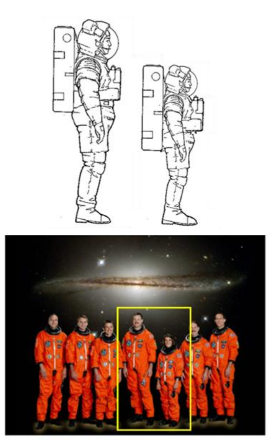


Figure 30. SPS Gateway uses fewer consumables.

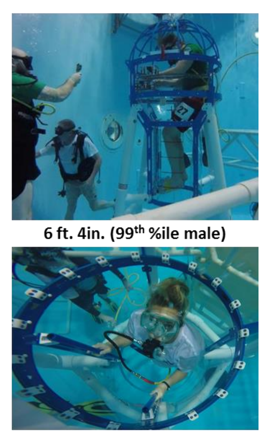
Sizing Extremes



ISS Inventory Required for Suit Sizing

Suit Part	Sizes	Each EVA	ISS invntry
Extravehicular Visor Assembly	1	2	2
Helmet	1	2	2
Communications Carrier Assembly	6	2	6
Hard Upper Torso	3	2	3
Upper Arm	1	4	4
Lower Arm	1	4	4
Gloves		4	8
Thermal Comfort Gloves		2	16
Waist Brief Assembly	5	2	4
Leg Assembly	1	4	4
Boots	2	4	4
Boot inserts	3	4	6
Liquid Cooling/ Ventilation Garment	7	2	4
Thermal Comfort Undergarment		2	16
Maximum Absorption Garment		2	10
Crew preference options (5)	1	2	
In-suit Drink Bag	1	2	3
Portable Life Support System	1	2	3
Display and Control Module	1	2	3
Cuff Check List	1	2	2
SAFER	1	2	2
		54	106

SPS One Size Fits All



Ingress/Egress

Figure 31. SPS eliminates on-orbit suit sizing inventory.

[21] http://www.unitedspacealliance.com/news/newsletters/issue066/Articles/CoverStory_ISS_Operations_ABridgetotheFuture.asp

visibility, reach and comfort. This has been confirmed through two series of neutral buoyancy test using 34 test subjects.

6. Tools

Different tools are required for suited EVA and SPS operations. For the most part, suited astronauts use the space-rated equivalent of earth tools, while the SPS positions a multifunctional tool head with a manipulator. Also, Gateway EVA tasks will be different than ISS. The NASA delivery sequence has the airlock arriving last and thus no suited EVA will be used for assembly operations. Instead, Gateway tasks will focus on servicing, repair and, as the outpost evolves, external science payloads and lunar spacecraft.

In the past, EVA equipment required for servicing amounted to a substantial payload. For example, on STS-103 (Mission 3A) for Hubble Space Telescope servicing 1182 kg and 2.6m^3 (2600 lbs. and 90 ft^3**)** were manifested for suits, tools, carriers, and consumables.[22] Hopefully, a Hubble-type servicing mission will not be required for Gateway so for this trade a more reasonable approach uses the tools identified the EVA Standard Interface Control Document. For this, 55 Generic Nominal tools and 32 Generic Contingency tools are used for ISS[23].

The SPS uses interchangeable end-effector tools. One end-effector is the 6.8 kg (15 lb.) Taurus robot (a grandchild of SRIs surgical robot) now being used for bomb disposal. Time is of the essence for both applications, so the system is specifically designed for rapid intuitive operations. This is an important attribute for EVA operations which is one of the reasons why the Taurus is an effective solution for Gateway. Along with tool head lighting and a vision system, the Taurus has haptic feedback for increased sensitivity. Figure 32 shows tools for both options. SPS tools are favored because they weigh less, are more versatile, have extended reach and match the anticipated Gateway EVA tasks.

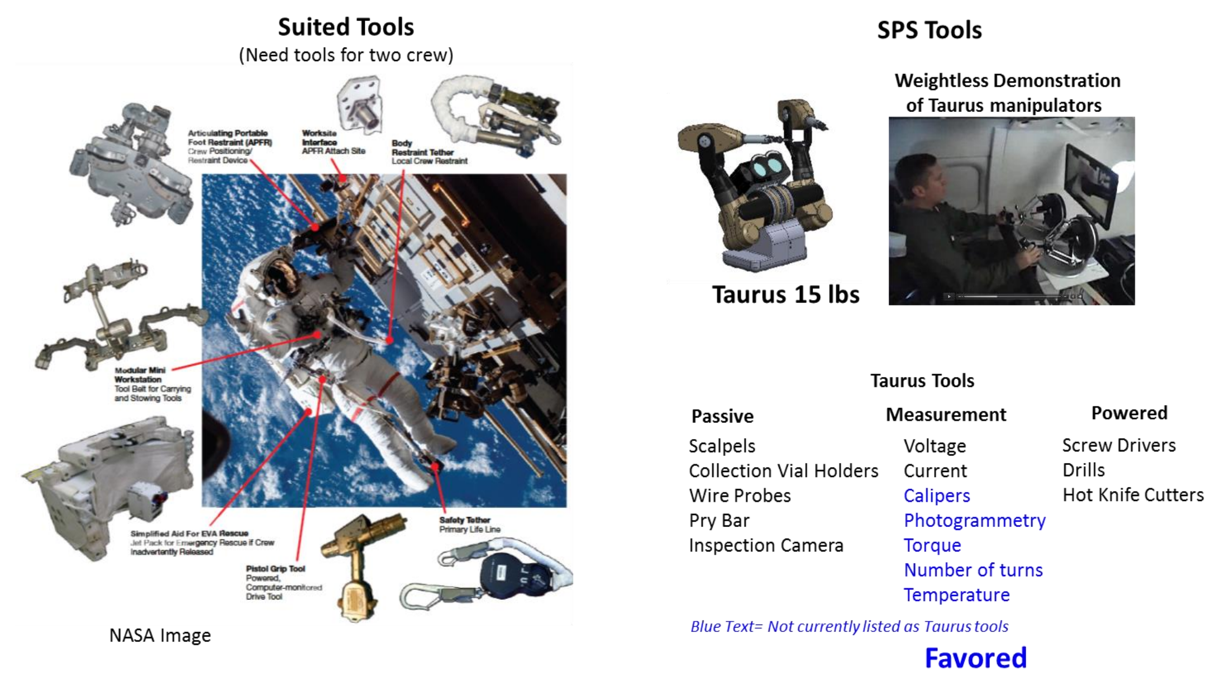


Figure 32. SPS tools weigh less and are better suited for Gateway servicing and repair tasks.

E. Gateway Objectives

The purpose of the section is to compare the EVA options to the Gateway objectives. NASA's web site states that Gateway.[24]

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[22] Advanced EVA Roadmaps and Requirements, Richard K. Fullerton, NASA/JSC, ICES2001-01-2200

[23] EVA Standard Interface Control Document, SSP 30256:001 Revision F

[24] https://www.nasa.gov/feature/deep-space-gateway-to-open-opportunities-for-distant-destinations

- Allows engineers to develop **new skills** and **test new technologies** that have evolved since the assembly of the International Space Station
- Developed, serviced, and utilized in collaboration with **commercial** and **international partners**

1. New Skills

Whether the Gateway uses the ISS EMU or a new suit for EVA it is not clear what new skills would be developed. Pre-breathing, hand-over-hand translation, operating from foot restraints would be common to both. On the other hand, because it has never been done before, new skills are required for SPS operations. Much will be learned about translation, manipulator operation, restraint, and the use of on board information system to assist in completing the task. The SPS option is favored for developing new EVA skills (Figure 33).

2. New Technologies

For suits, Gateway could be the venue for verifying new PLSS technologies in the weightless environment. A new rear-entry suit may be classified as a new technology, but the Russian rear-entry Orlan suit on ISS is operational so this is not a new technology rather, a different design. SPS is a new capability with select new technologies which include the information management system, the Taurus robot and, components within the air management system. So, in terms of new technologies that have evolved since the assembly, the SPS is more in line with this objective than suited operation.

3. Commercial

NASA's has always provided space suits and with the current investments into new suit development, it appears that Gateway's suit would be government provided and not a commercial product. To date, SPS development has been all commercial and the intention is that this would continue in coordination with NASA, but largely as a commercial venture. Consequently, for EVA, the SPS represents the Gateway commercial objective better than space suits.

4. International partners

There is much uncertainty and speculation in comparing what role the international partners would have in either option. It is possible that the airlock could be provided by an international partner. Equally, it is possible to have an international partner provide the berthing vestibule or other components of the SPS. Therefore, at this stage of development, there are no clear discriminators to favor one option over the other.

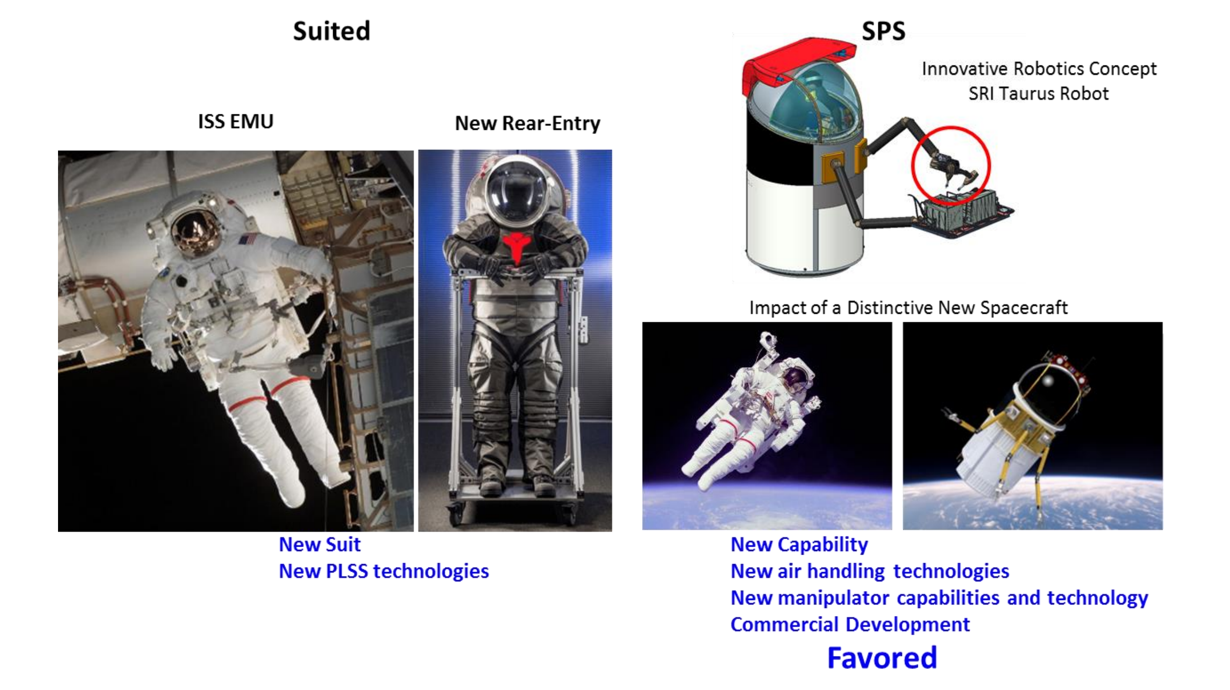

Figure 33. SPS new technologies and commercial development reinforce Gateway objectives.

F. Impact on Gateway Elements

This section addresses the physical accommodations required of Gateway modules to be compatible with either suited or SPS EVA. This is important because ISS modules were required to comply with many EVA requirements including translation paths geometry, handrail structural loads, surface finish to avoid glove damage, signage, and work site interfaces. With this experience it is reasonable to assume that a suited Gateway would have the requirements.

1. Interfaces

Schematic diagrams were used to compare interfaces for a Gateway with an airlock versus one with a SPS vestibule. NASA's configuration shows an airlock module that resembles the ISS Quest two chamber airlock, but it is possible to have the equipment lock function incorporated into an adjacent module. Regardless, the biggest distinction between the options is that, with the exception of certain tools, 2 suits, 2 SAFERs, LCVGs, resizing components, and servicing equipment must be stored inside the Gateway. For the SPS only servicing equipment is inside.

It is still very early in the development of Gateway, but if the International Docking System Standard (IDDS)[25] is used to connect airlock elements then special arrangements are required for the fluid connectors because these are not included in the current design. This feature is essential for suited EVA because the EMU must be connected to an umbilical for cooling while the astronauts are in the crew lock. Furthermore, utilities at the interface determine the location of air lock pump and accumulator. The SPS vestibule is delivered attached to the IDDS bolt hole pattern. It also requires access to utilities, but only for recharging systems between excursions. For this, drag-throughs utilities connect to a SPS servicing panel otherwise the Gateway hatch is typically closed. A closed hatch still allows for IDDS data and power connection to the SPS. Overall, SPS interfaces are less complex than for the suited airlock, so this option is favored (Figure 34).

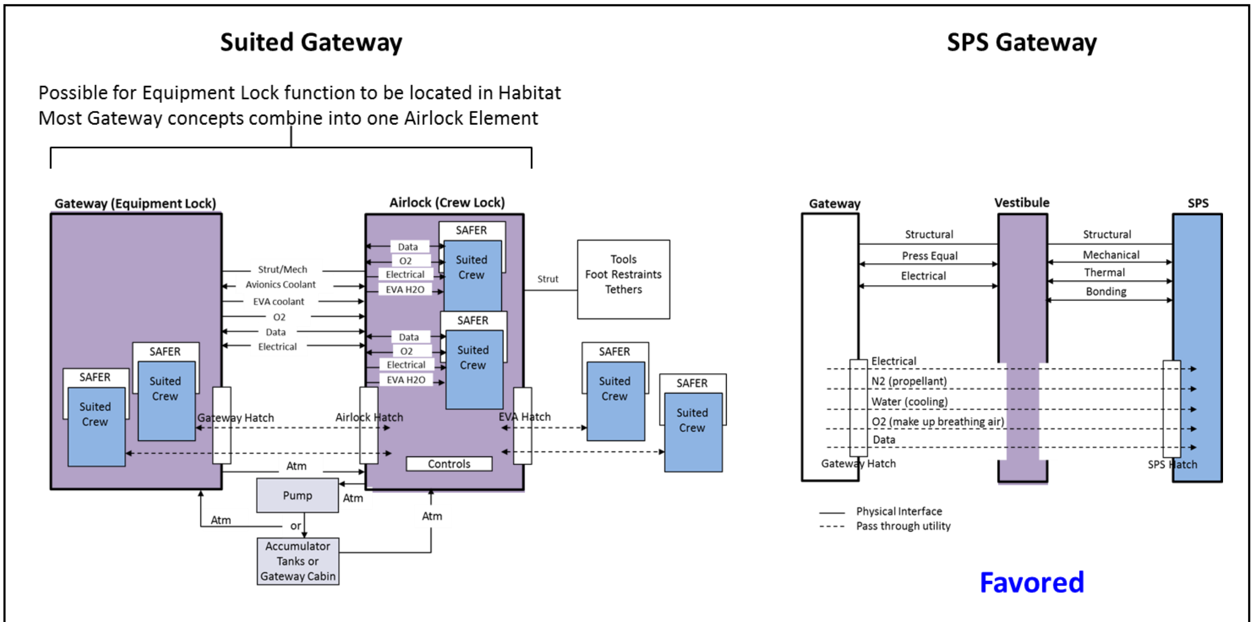

Figure 34. SPS Gateway interface is less complex.

2. Translation Aids

For suited EVA, Gateway must provide translation paths from the airlock to locations of anticipated maintenance as well as to areas potentially needing access. Again ISS sets the pattern, including longitudinal and circumferential handrails on the surface of habitable modules and on adjacent structure (Figure 35). Handrails must be anchored into structure designed to withstand a load limit of 978.6 N (220 lb.) and the secondary structure within 24 in. must be able to withstand a 556 N (125 lbf) inadvertent kick load. Because the SPS flies to the work site without the need for translation structure and hardware, it is the favored option.

[25] International Docking System Standard, Revision E, October 2016

3. Work Site

In order for suited EVA crew to be effective at the work site they need to have both hands free. Foot restraints are the accepted method of freeing up both hands and reacting work loads to structure. Because the objective of the foot restraint is to properly position the suited astronaut to do work, they must be adjustable for all crew. Including the height adjustment and articulation, foot restraints can weight 50 lbs. The direct impact to Gateway elements is securing the foot restraint work site interfaces (WIFs) in predetermined locations. SPS uses zero torque tools, the propulsion system and anchor points mounted to Gateway structure. The SPS anchor points are the equivalent of the suited EVA WIF. Considering this neither option is favored over the other for the worksite impact to Gateway.

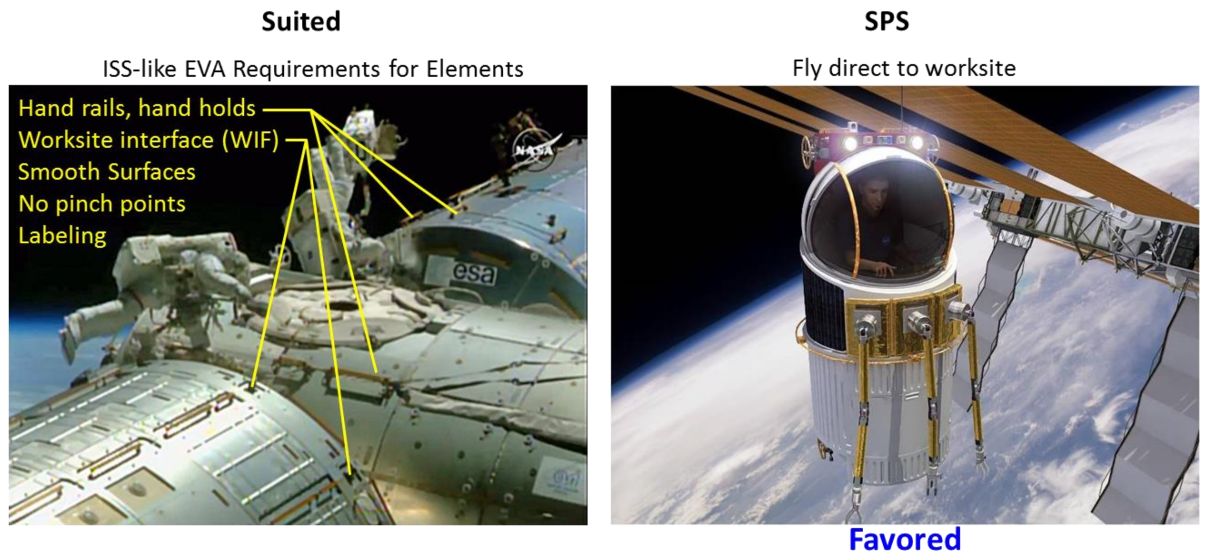

Figure 35. No impact to Gateway element for SPS translation.

4. External finish

Typically, there would be no reason to place finish requirements on external structure. However to avoid cutting EVA gloves or snagging tethers, there are requirements for deburring aluminum, eliminating sharp edges and minimizing potential snag points. Because the SPS does not require any particular finish treatment SPS, it is the favored option.

G. Acquisition

Acquisition includes the number of elements or hardware components required to support EVA, the number of launches, type of acquisition, training, and estimated cost.

1. Elements

To support a suited Gateway, at a minimum it takes 2 EMUs, 2 SAFERs, 2 EMU umbilcials and an airlock with a pump. In addition 2 APFRs and 12 WIFs, 42 handrails, 4 tethers, and 2 BFRs would be required. For tools, 2 tool caddies, 2 pistol grip tools, 55 generic tools and storage are included. Also, there needs to be an oxygen pre-breathing system, provisions for servicing and recharge PLSS consumables, and suit sizing equipment.

The SPS Gateway needs to have at least one SPS, a berthing vestibule, servicing equipment, and umbilicals for recharging consumables. It is possible to bring a second SPS to Gateway and either alternate using the same vestibule or outfit a berthing port with a second vestibule.

Because SPS requires fewer elements to enable EVA it is preferred of the suited option.

2. Launches

As discussed earlier, the SPS option is achievable with 3 launches compared to 4 for suited EVA. This not only reduces cost and risk but enables an earlier operational capability. The SPS is favored because fewer launches are required to achieve EVA capability.

3. Acquisition (GFE/Commercial)

New spacesuits are currently being developed by NASA so it is safe to assume that if suits are used on Gateway, they will be provided by the government. The question is what suits will be provided. Because there are only 11 ISS EMUs and 4 are on ISS it is not certain that these are enough to support ISS through 2024. If not, NASA can place an order for additional ISS EMUs to be used for Gateway or use a new weightless suit. Clearly, there is less risk using the ISS EMU but this design was developed over 40 years ago and does not fulfill NASA's Gateway objective for new skills and technology. Also, with respect to cost, in 2017 the Office of Inspector General expressed dissatisfaction of NASA's new suit development stating, "Despite spending nearly $200 million on NASA's next-generation spacesuit technologies, the Agency remains years away from having a flight-ready spacesuit capable of replacing the EMU or suitable for use on future exploration missions[26]." Using the SPS would eliminate integrating costly weightless requirements into the new suit concept only to produce the two new suits required for Gateway.

A commercially developed SPS avoids the government procurement process and is motivated to control expenses thus reducing the cost to the government. Furthermore, the one design of the SPS produces multiple copies whereas, a spacesuit is a complex system of parts further complicated by sizing variations and operations in two very different environments. The less complex SPS reduces the Design, Development, Test and Evaluation (DDT&E) and recurring cost for EVA.

4. Training

Methods and cost associated with EVA training are very different for suited EVA and SPS operations. As mentioned above, neutral buoyancy is favored for suit training. For this, there is the expense of additional training suits, the use of the NBL facility, plus new Gateway neutral buoyancy hardware must be included in the overall cost. The neutral buoyancy water environment incurs an additional expense because facilities and equipment must be continuously maintained and testing supported by certified scuba personnel.

Like aircraft, SPS astronauts are trained in a simulator allowing low cost, repeated operations without the safety issues of neutral buoyancy training. This proven approach to training allows high risk contingency operations to be conducted without concern for astronaut safety. Environments can be rapidly changed and it is possible for remote lap-top operations for Gateway proficiency training. There is no need for additional Gateway training hardware and while it may require as many as four additional neutral buoyancy suits, only one SPS training simulator is required.

5. Estimated Cost

The estimated cost of suited EVA for the Gateway is over ten times of that for using the SPS. Suited EVA cost is estimated to be $718.8 M and for the commercial SPS the cost to the government is $61.2 M. Regardless of the phase of the program, cost can always be argued. The cost of suited EVA is based on acquiring new ISS EMUs and not a new suit program and it uses recently published launch costs for the Atlas V, not the SLS. It is assumed that the SLS will cost more to launch. What the estimates say is that even if suited EVA is cut in half and the SPS doubled, there is still over a $200 M gap.

VI. Findings

Of the 44 areas compared, suited EVA was favored once, 7 areas tied, and SPS EVA was favored in 36 areas. Why such a large difference? One possibility is that suited EVA has never been compared to a different capability. Until now, EVA trades have focused on modifications to the traditional suit design rather than a different way to do EVA. The SPS is a spacecraft specifically designed for weightless space operations. Planetary suits represent the biggest demand and greatest technical challenge for NASA engineers. The current approach to combine very different weightless and planetary requirements into a common suit solution is a significant challenge which will certainly complicate the design and drive costs higher. There is an obvious opportunity for subsystem commonality, but separate solutions represents the best path to optimal performance at the lowest cost.

[26] NASA Office of Inspector General, NASA's Management and Development of Spacesuits, April 26, 2017, IG-17-018 (A-16-014-00).

Full Disclosure

It should be noted that this trade analysis was conducted by Genesis Engineering Solutions, the company that is developing the SPS. Although unintended, it is possible that the SPS was favored or perhaps some of the potential negatives have been under-emphasized. To ensure that the results are as accurate as possible, the authors invite knowledgeable individuals or companies to contribute citable references to help refine or correct trade results.

References

Finger, B.W., Zimmerman, B. Bower, C., Griffin, B. and Woo, C., "A Tailored Life Support System for the Single-Person Spacecraft," 48th International Conference on Environmental Systems, July 8-12, 2018, Albuquerque, New Mexico, ICES-2018-342

Fullerton, R. K., "Advanced EVA Roadmaps and Requirements," ICES01-2200

Griffin, B., Rashford, R., Lutter, J., Woo C., Gaylin, S., Bousquet R., Klappenberger M., Belz M., Harvey D., Wolf E., Stephens M., and Finger B., "Single-Person Spacecraft: Progress Toward Flight Testing," AIAA Space Forum, Orlando, FL, September 12-14, 2017, AIAA 2017-5103

Griffin, B. N., "Benefits of a Single-Person Spacecraft for Weightless Operations," 42nd International Conference on Environmental Systems, San Diego, CA, July 15-21, 2012, AIAA 2012-3630

Griffin, B. N., Dischinger, C., "Low Cost Space Demonstration for a Single-Person Spacecraft," 41st International Conference on Environmental Systems, July 17-21, 2011, Paper no. AIAA 2011-5247

International Space Station, Robotics Group, Robotics Book, JSC 48540

International Deep Space Interoperability Standards, Draft C, February 2018

Looper, C., and Ney, Z., "Extravehicular Activity Task Work Efficiency," SAE 2005-01-3014

Manned Maneuvering Unit, Space Shuttle Program, Operational Data Book, July 1985, Volume 1, Martin Marietta MMU-SE-17-73 Rev. B, NAS9-17018

Manned Maneuvering Unit, Design and Performance Specification, February 1978, Martin Marietta MCR-78-500, NAS9-14593

NASA's Management and Development of Spacesuits, NASA's Office of Inspector General, Report no. IG-17-018, April 26, 2017

NASA, "Significant Incidents and Close Calls in Human Spaceflight: EVA Operations," July 27, 2016

Opperman, R.A, et al,,"Probability of Spacesuit-induced Fingernail Trauma is Associated with Hand Circumference," Aviation Space Environmental Medicine, Oct, 2010

Pasztor, Andy, "U.S., Israeli Space Agencies Join Forces to Protect Astronauts From Radiation," Wall Street Journal, April 17, 2018.

Schaezler,B., Cook, A., Leonard, D., and Ghariani, A., "Trending of Overboard Leakage of ISS Cabin Atmosphere," AIAA 2011-5149

Scheuring, R., "Shoulder Injuries in US Astronauts Related to EVA Suit Design," NASA Flight Surgeon, DO, MS, FAsMA, FAAFP, Aerospace Medical Association, May 11, 2012

Tian, Y., et al, "Effects of EVA Gloves on Grip Strength and Fatigue Under Low Temperature and Pressure," Applied Ergonomics, Vol. 53, Part A, March 2016, pp 17-24

Walz, C. and Gernhardt, M., "Extravehicular Activity – Challenges in Planetary Exploration," 27 February, 2008, Third Space Exploration Conference and Exhibit, Denver, CO