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Single-Person Spacecraft Progress toward Flight Testing

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Someday, astronauts will have safe, any-time access to space without the risk of the "bends" or need of an airlock. With recent progress in the development of the Single-Person Spacecraft (SPS), "someday" could be very soon. This will be a welcomed improvement for servicing the aging International Space Station (ISS), satellites, telescopes, habitats, the deep space Gateway, and Mars mission vehicles. Today, it takes a long time for suited astronauts to get to the work site but with SPS there is no lengthy pre-breathe, depressurizing an airlock, or hand-over-hand translation. Instead, astronauts fly directly to the site spending more time on the job rather than in preparation or translating back and forth. Furthermore, the SPS is designed for crew autonomy providing an information-rich cockpit with displays and controls to assist with infrequent and unplanned tasks. This new capability is moving closer to reality and the purpose of this paper is to describe the recent engineering accomplishments leading to flight testing.

Nomenclature

AMS	=	Air Management System
ARS	=	Air Revitalization System
CO	=	Carbon Monoxide
CO2	=	Carbon Dioxide
CAD	=	Computer Aided Design
EDGE	=	Engineering DOUG Graphics for Exploration
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
ISS	=	International Space Station
MEL	=	Master Equipment List
MMOD	=	Micrometeoroid/Orbital Debris
PDU	=	Power Distribution Unit
PSI	=	Pounds per Square Inch
SPS	=	Single-Person Spacecraft
UAT	=	Underwater Astronaut Trainer

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I. Introduction

CONCEPTS for a single-person spacecraft can be traced to Werner von Braun's Bottle Suit (See Fig. 1) and until now, few have progressed beyond preliminary design. The current private development of the Single-Person Spacecraft (SPS) has made considerable progress in design, analysis, and test with plans for an initial robotic flight demonstration to be followed by piloted applications.

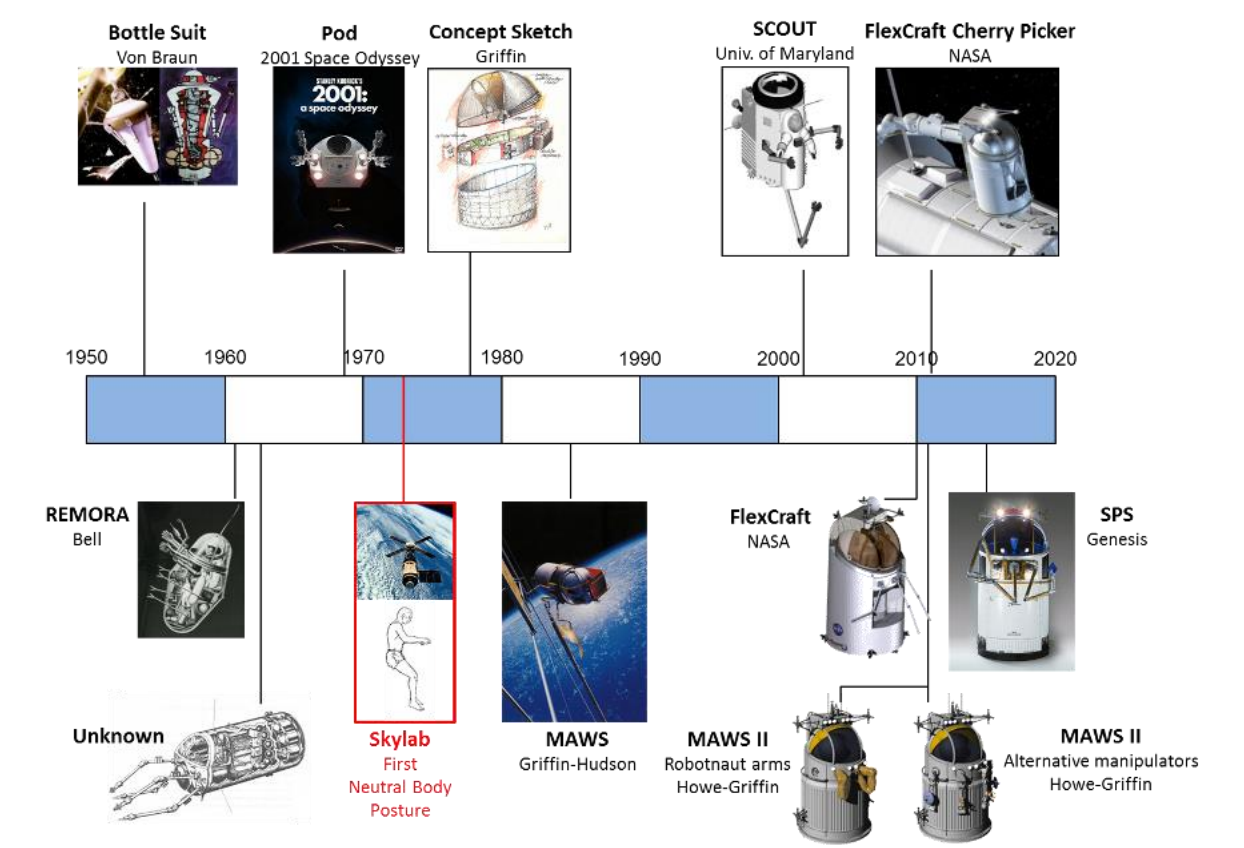


Figure 1. SPS is the latest, most developed single-person spacecraft concept.

II. SPS Overview

The SPS provides external operations for a broad range of tasks including the inspection and servicing of the International Space Station (ISS), telescopes, satellites and habitats, as well as exploration of low gravity moons such as Phobos. It can be piloted or tele-operated and because the cabin pressure is the same as the host vehicle, it allows immediate access to space without pre-breathing or the use of an airlock. The SPS propulsion system means the crew can get to and spend more time at the work site rather than translating back and forth hand-over-hand. Sized for the full astronaut population, it provides a shirt sleeve, cockpit-type environment complete with the displays and controls necessary for flight operations and task management. The SPS is equipped with lights, cameras, and interchangeable manipulators for dexterous servicing or sample collection.

III. Development

For the development of human spacecraft, the acquisition process has created a culture of dependency that relies on government initiative and responsive contractors. Contracts are evaluated and awarded based on compliance to requirements. In the case of private development, the contractor takes the initiative without a set of formal customer requirements. For some, this is paralyzing, others find it liberating, regardless it doesn't come without a change. Institutions resist change; it is disruptive by its very nature. So how do private contractors design and build spacecraft? What needs to be unlearned? What processes should be retained? The private development of the SPS has struggled with these issues eventually adopting four constraints to help guide decisions that otherwise would be unbounded and counter-productive. For SPS these are: a. Design-to-availability, b. Lite Systems Engineering, c. Ready! Fire! Aim!, and d. Bare Bones.

A. Design-to-Availability

The good news is that most of the necessary SPS systems have flown in space but that doesn't mean they are sitting on the shelf. Design-to-availability offers benefits of reduced design, development, test, and evaluation but introduces procurement challenges. This emphasis on procuring components versus making them requires a flexible design able to accommodate changes resulting from unacceptable delivery times or very high costs. This approach comes with an understanding that some parts will need to be made, but forces the question to avoid development risks.

B. Lite Systems Engineering

Because many space programs are large and complex with many interfaces and a long development times they benefit from a comprehensive systems engineering approach. One lesson from SPS is that systems engineering does not have to lead or dominate. The SPS Lite approach focuses on generating solutions then feeding these back into the evolutionary spiral. Furthermore, not all decisions need trade off analyses, instead with this approach heuristics, engineering judgment, and reliance on proven performance play an important role in moving the design forward. Another reason Lite systems engineering is the best fit is that SPS does not have a customer providing specific requirements. Instead, like airplanes, automobiles, phones, and other commercial ventures, SPS development is inspired by offering a new capability focused on a market for safe, efficient external space operations.

C. Ready! Fire! Aim!

SPS slightly alters the conventional sequence of Ready! Aim! Fire! with the intent of accelerating the decision making. This program approach is not as reckless as it sounds. With good intentions, sometimes, excessive resources are spent creating and refining requirements only to be changed as the product matures. Establishing and maintaining flow-down, traceability, and configuration is good discipline but it drains resources and makes the project less flexible. Therefore, understanding the risk, SPS has adopted a Ready! Fire! Aim! approach meaning it's better to decide and then adapt, rather continually than rework requirements.

D. Bare Bones

Somehow, the development process invites making good, better. If better results in weighing more or being more complex, then for the SPS it isn't better. In contrast, the SPS approach strives for the simplicity of *lagom*, a Swedish term meaning enough, sufficient, adequate, just right. Voltaire was a little more explicit stating that "better is the enemy of good." With this in mind, the goal for the initial SPS is bare bones…functional without all the tempting enhancements that would make it "better." This is easier said than done requiring ever-vigilant management along with creating a culture of good enough.

IV. Design

A. Baseline Configuration

The SPS configuration (Figure 2) consists of a pressurized crew enclosure; an external equipment bay bounded by a Micrometeoroid/Orbital Debris (MMOD) shielding skin; and an overhead 'crown' assembly. The bottom of the SPS contains a berthing/docking mechanism and hatch for crew translation ingress and egress.

1. Crew Enclosure

The enclosure is comprised of a clear hemispheric canopy providing broad field of view, a large diameter upper torso allowing astronaut arm movement, and a smaller diameter lower torso for foot restraint and crew ingress/egress. Because SPS operations are more like a helicopter than a commercial airliner, the large canopy is ideal for moving the head to improve line-of-sight visibility. The SPS enclosure is designed around the weightless neutral body posture and is sized to accommodate the entire Astronaut population.

2. External Equipment Bay

The unpressurized volume between the crew enclosure and the MMOD layer serves as space for packaging the external subsystems. Thrusters, propellant tanks, batteries, and a multifunctional tool drawer are connected to four radial longerons. An extendable "drawer" below the manipulators can be tailored to the mission for holding spares, tools or samples.

3. Crown and Visor Assembly
As the name implies, the crown sits on top of the SPS secured to structural rails that arch over the pressurized canopy. It serves as the structure for the upper propulsion thrusters, is an enclosure for avionics components, and has lights and cameras attached to the forward face. Similar to the space suit helmet, there is a protective outer layer and crew adjustable visors for sun control.

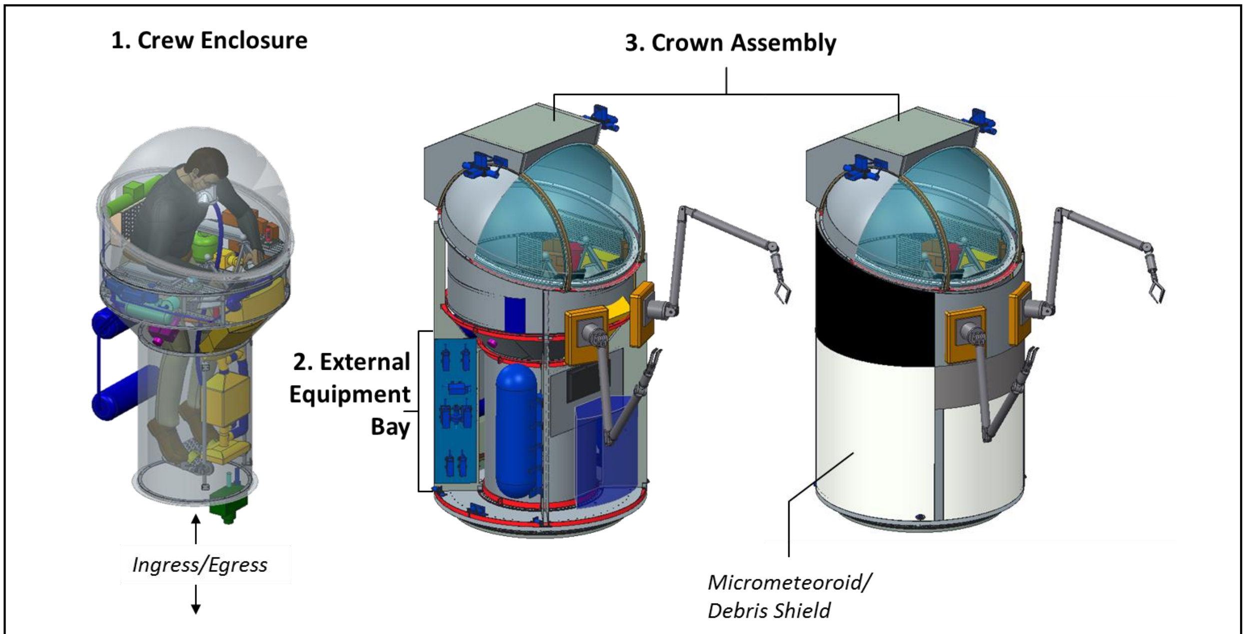


Figure 2. Major elements of SPS configuration.

B. Master Equipment List
All SPS components are bookkept in a Master Equipment List (MEL). This is one of the most important tools used in managing the spacecraft development because it includes mass properties and a mass growth allowance to account for uncertainty. It also includes assumptions or rationale for each line-item. Currently, the MEL is

Mass Summary

ITEM	Basic Mass (lbs)	MGA (%)	MGA (lbs)	Predicted Mass (lbs)
Mass Breakdown				
Structures / Mechanism	610.28	14.3%	87.32	697.59
Thermal	70.15	15.1%	10.63	80.77
Power	90.96	8.4%	7.64	98.60
Air Handling	138.68	11.8%	16.30	154.97
Propulsion	129.38	9.0%	11.60	140.98
Avionics and Software	21.12	11.9%	2.51	23.63
Internal Layout	14.11	13.7%	1.93	15.19
Dry Mass	1074.7	12.8%	137.9	1211.8

Master Equipment List

3.8	C&DH			
	3.8.1	MEB		Y
	3.8.2	Manipulator Board		Y
3.10	Internal Layout			
	3.10.1	**Flight Deck Bridge**		
		3.10.1.1	Main Panel	Y
		3.10.1.2	Support Plate	Y
		3.10.1.3	Translation Aid	Y
		3.10.1.4	Spray Bar	Y
	3.10.2	**Starboard Mounting Asssembly**		
		3.10.2.1	Primary Support Beam	Y
		3.10.2.2	O2 Support Assembly	Y
		3.10.2.3	Nitrox Support Assembly	Y
		3.10.2.4	Secondary Support Beam	Y
		3.10.2.5	Support Flange	Y
		3.10.2.6	Closeout Hinge	Y
		3.10.2.7	Closeout Cover	Y
		3.10.2.8	Pressure Relief Mounting Plate	Y
	3.10.3	**Port Mounting Assembly**		
		3.10.3.1	Primary Support Beam	
		3.10.3.2	Valve S	

Figure 3. SPS Mass Properties and Master Equipment List.

intentionally inclusive listing alternative components for the same function. This approach provides a quick side-by-side comparison providing an ongoing mass sensitivity analysis to be used in determining the final selection. More than an accounting record, the MEL is also a tool used to identify the areas most likely to result in the greatest weight reduction. Figure 3 shows the SPS current mass breakdown which is dominated by structure, propulsion and the air management system and a section of the MEL.

V. University-level Internal Design Competition

Early in the design process, the SPS team invited universities to participate in a competition to create concepts for the interior of the SPS. Participating universities were asked to layout the dispalys/controls, crew restraints, lighting, air flow and other aspects of the interior design. Participants were required to design with neutral body posture in mind and were constrained to specify catalog parts to ensure the design would be feasible given existing technology. The submission of each university was scored by a total of 10 jurors including an astronaut with EVA experience and engineers with backgrounds in human factors, aerospace engineering, and robotics. The Florida Institute of Technology was awarded the Grand Prize and the Superior Design prize was awarded to University of Houston. (See Figure 4)

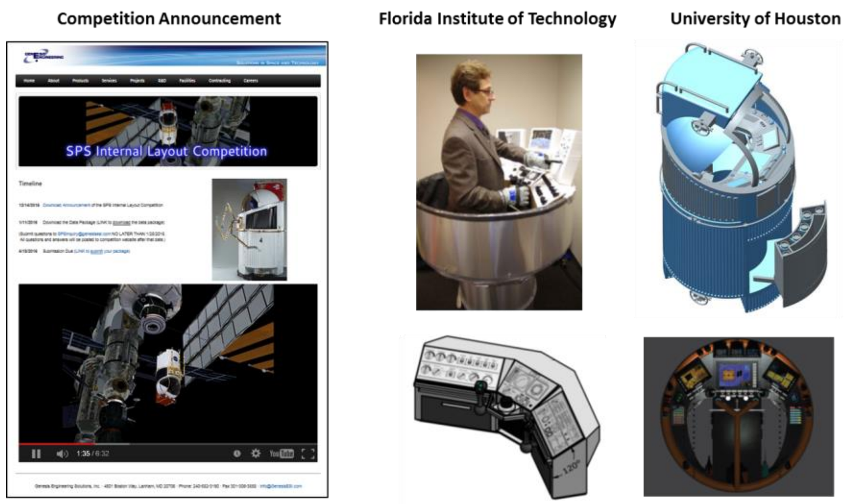


Figure 4. Winning Design Competition Entries.

VI. Mockup

A SPS high fidelity mockup (Figure 5) was constructed to provide a full-scale physical model for human factors assessments and explore alternative subsystem packaging concepts. As a concession to earth's gravity, the mockup is equipped with open an portion in the rear allowing users to step inside and an internal lifting platform to assess different eye-point positions and evaluate reach envelopes. It is equipped with a touch screen display capable of controlling internal and external lights, a pilot camera, fan, and the lifting platform. If manual control is desired or there is computer failure, a switch panel allows the user to manually override the digital control. Finally, the high

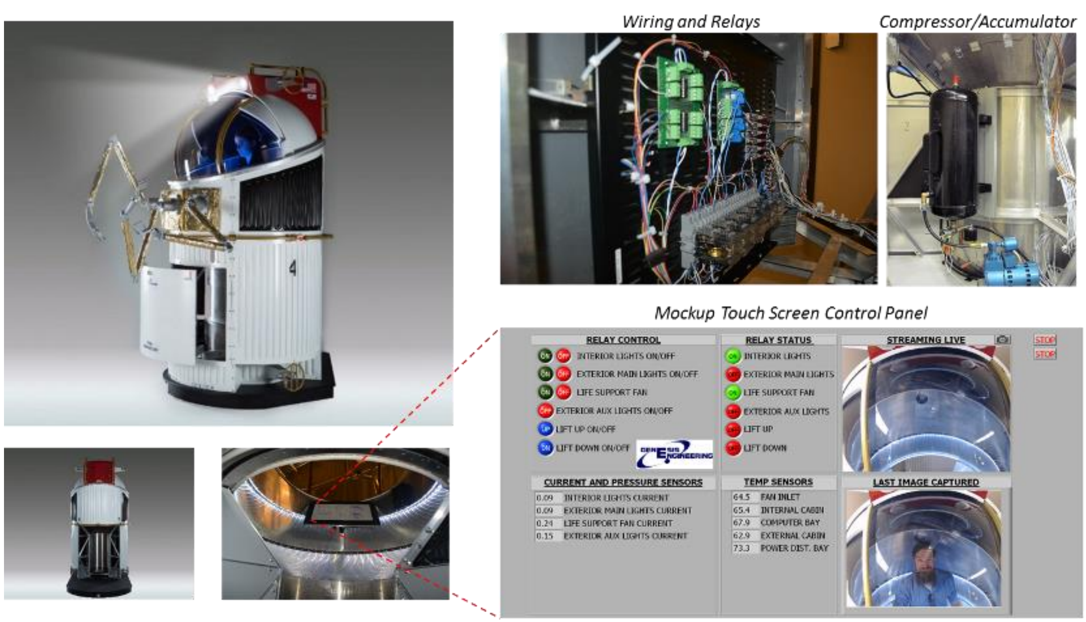


Figure 5. SPS mockup includes lift for positioning the pilot to desired eye location.

fidelity mockup is a valuable tool for presenting the overall configuration and allowing individuals to get inside and sense what it would be like to fly the SPS.

VII. Flight Simulator

The SPS approach stresses having a flight simulator at the beginning of the development process to be used as a tool for integrating engineering and operations analysis. For this, another SPS shell (Figure 6) with internal lifting platform was constructed with three wrap-around monitors placed just outside the canopy. The simulator is valuable at the front end because flight characteristics can be evaluated qualitatively and quantitatively as the mass properties, propellant usage, and flight performance of the design change. Ultimately, this may influence the location of subsystems, thrusters, and mode of flight control.

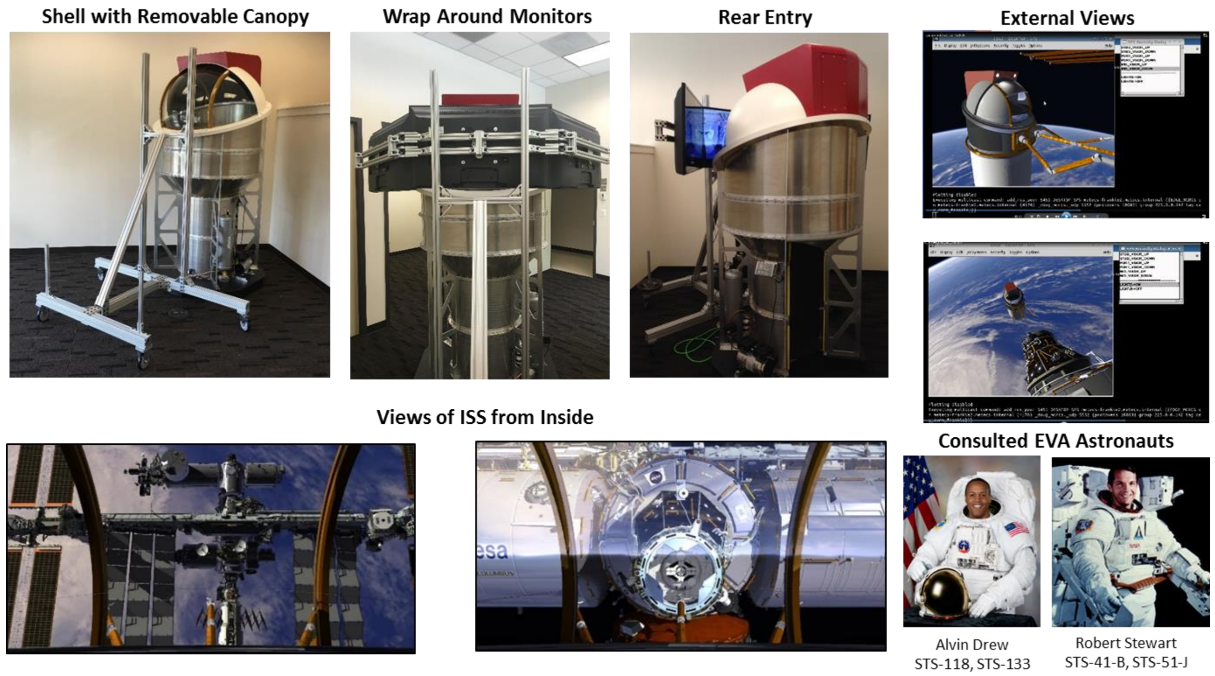


Figure 6. The flight simulator is a key element of the SPS development.

As development continues, the simulator will take on more ambitious roles. Flight hardware will enter the simulation loop for verification of avionics and control. In a mature state the simulator will act as a flight trainer, representing a flight-like configuration.

Because of their experience in developing NASA simulation software, Genesis Engineering contracted with METECS to help create the SPS flight simulator. The simulation underpinnings run on the Trick platform. Trick is a versatile platform for flight simulation and is capable of modeling nearly every spacecraft subsystem. The graphical frontend of the simulator is accomplished using EDGE (Engineering DOUG Graphics for Exploration), a package that includes features for graphical modeling, scene building, and a rendering. The SPS implementation of DOUG includes a high-fidelity graphical model of the International Space Station as a flight environment. Because about half the ISS orbit is in shadow, the simulator has been used to model SPS lighting in order to assess illumination for servicing tasks and berthing.

1. Hand Controllers

During the early phases of development the SPS simulator was controlled by keyboard inputs. Now, joystick controllers have been installed in the simulator serving as an approximation of the flight controls. The simulator is being used to determine the optimal mounting location; for now they are on either side of the pilot in the front of the simulator enclosure.

2. Flight Model

The flight model represents a first pass approximation of the flight characteristics of the SPS. The model uses the mass properties generated by the latest CAD version of the SPS. Thruster placement, thrust, and specific impulse are all configurable. Attitude hold is achieved by individually halting rotation about each axis, using thrusters until a floor value is met, then rotation rates are zeroed.

3. Fuel Consumption

Propellant tank pressure is tracked throughout flight. Tank volume and fill pressure, and minimum pressure are user adjustable and have been edited to replicate the baseline tanks and pressure regulators used in the SPS cold gas propulsion system.

4. Testing and Data Collection

Trick allows for tracking and logging of data from the simulation. The development of fuel consumption tracking and a more realistic flight model allows for coarse tests to evaluate the fuel capacity and flight characteristics of the current SPS design. (Figure 7) For example, SPS excursion time and fuel consumption was recorded for three engineers performing the same ISS servicing task. Results were quite different leading to a decision on pulse versus continuous thruster control.

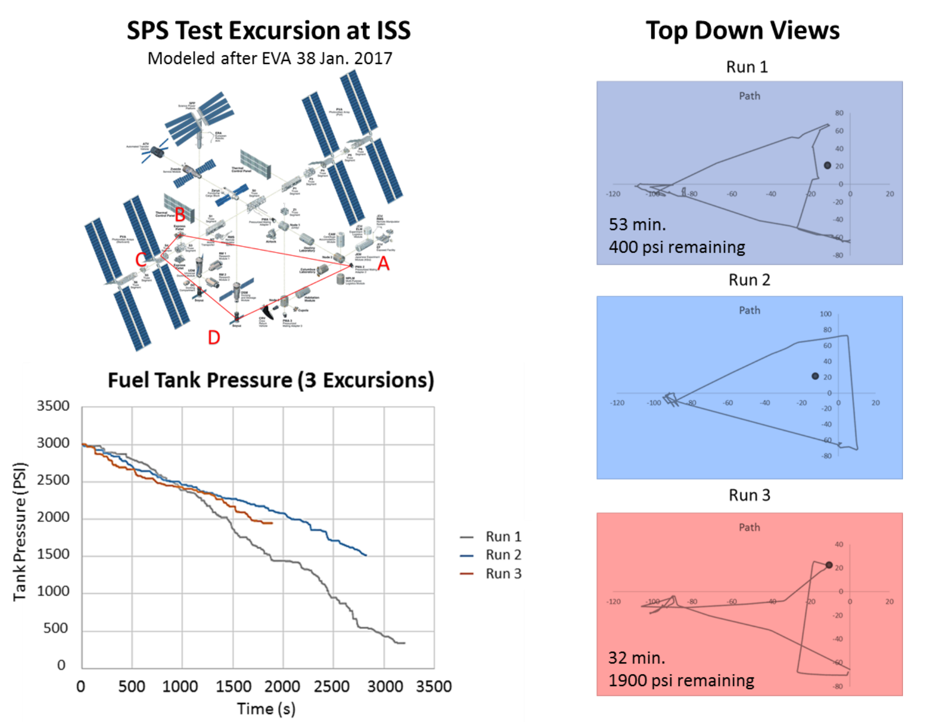


Figure 7. Propellant usage from three SPS simulated ISS excursions.

VIII. Internal Design Review

It is a good practice to get a concept review from outside experts at a time when design changes can be incorporated without significant cost or schedule impact. With the SPS, subsystem definition had matured beyond the university design competition so the time was right for a review of the latest concept. For this, a panel of space professionals was invited to review and comment on the interior layout of the SPS. Panel members brought experience in designing, building, and operating flight hardware for human missions. An astronaut added flying experience to the SPS controls review and provided comments based on the realities of EVA operations. Following a presentation of the internal layout, comments were recorded and organized into six categories: Flight and Controls, Visibility, Restraints, Displays, Air Management, and General. In summary, the panel members favored the wrap around, Apache helicopter geometry of the flight deck (Figure 8) and excellent visibility provided by the large canopy canted at a 15 degree slope. Furthermore, the type and location of flight and manipulator controllers (Figure 9) was reviewed favorably. There was concern that the foot restraint may cause leg muscle fatigue and discussion regarding the usefulness of a waist restraint. Regarding the mode of flight control, a computer assisted pulsed thruster operation was recommended over continuous input. This has been confirmed using the SPS flight simulator.

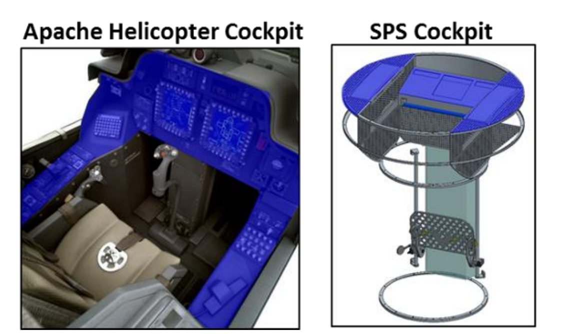


Figure 8. Cockpit inspired by Apache helicopter.

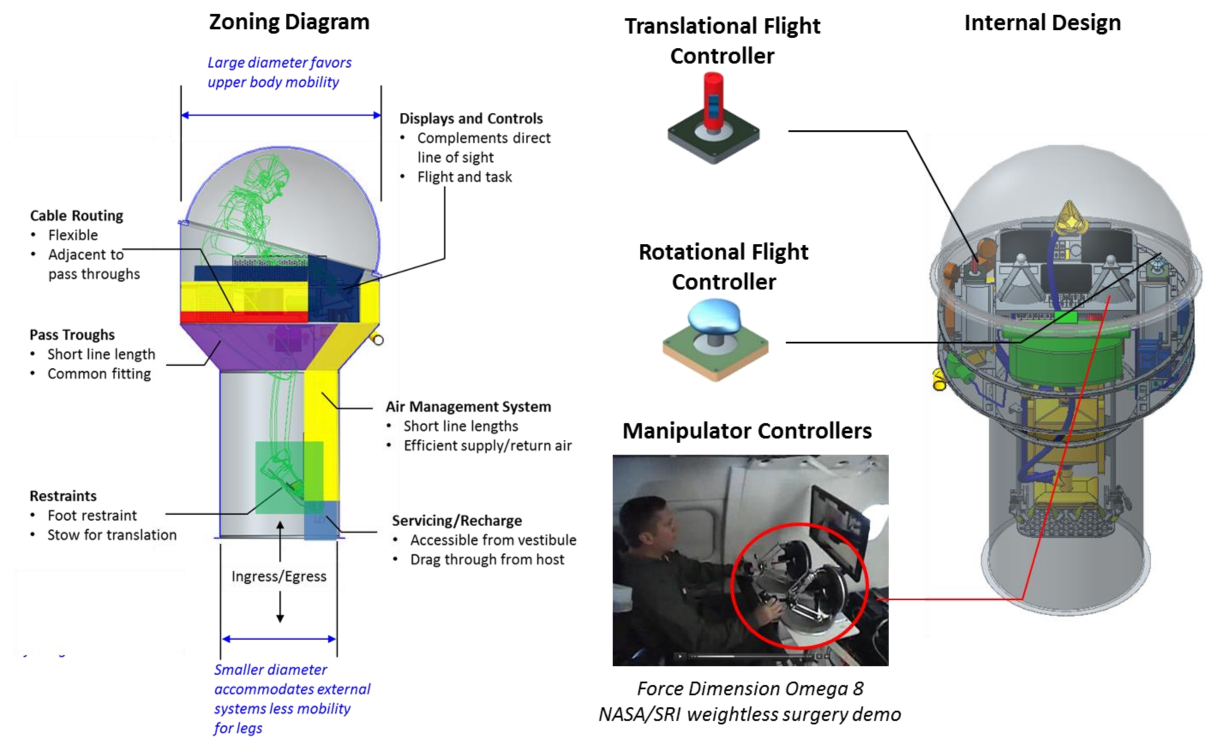


Figure 9. Separate SPS flight and manipulator controllers integrated into the Flight Deck.

IX. Testing

A. Neutral Buoyancy

To get in and out of the SPS the astronaut must translate through a 24 inch (0.6 m) diameter cylinder. This, along with other internal features unique to weightless operation needed to be verified before the design could proceed. Neutral buoyancy was used to simulate the SPS weightless environment assessing not only restrictive internal dimensions, but translation aids, reach, and visibility (See figure 10). For this, Genesis Engineering built a specific neutral buoyancy SPS mockup and partnered with the US Space and Rocket Center in Huntsville, Alabama using their Underwater Astronaut Trainer (UAT). Two series of tests were completed covering five testing days

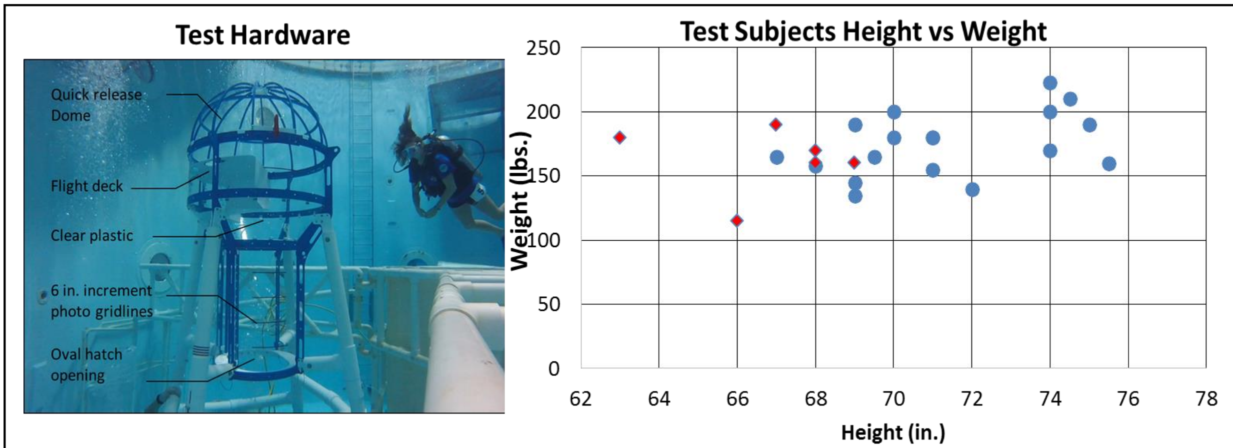


Figure 10. Tests used Neutral Buoyancy Hardware and Subjects that encompass Astronaut Population

with a total of 34 test subjects. The qualified test subjects ranged in stature from the 34th percentile (63 in., 1.6 m) female to the 99th percentile (75.5 in., 1.9 m) male. Although the lowest percentile female was not represented, the tests were considered legitimate because the concern regarding restrictive access is most sensitive for large males.

Ingress/Egress, hatch opening size and flight deck geometry

Genesis Engineering contracted Cardinal Scientific to construct the neutral buoyancy test article for the first series of tests. The neutral buoyancy test article was different because it had to operate in water with a high chlorine content, restrict mobility, allow visibility of test subjects for safety and test documentation, and allow rapid egress in case of an emergency. The resultant design is a cage-like powder-coated aluminum frame lined with clear polycarbonate complete with calibration marks for photographic documentation (Figure 11). Hatch options were represented by the 24 inch (0.6 m) diameter lower torso opening and a removable oval hatchway. Based on the winning design from the university internal layout design competition, a fan-shaped flight deck was installed. To represent the canopy, an open framed caged dome was constructed. The open frame design avoided problems of trapped scuba bubbles. Furthermore, the dome included a pair of quick-release mechanisms operated by the test-subject or safety divers enabling rapid removal and access to the test subject. The objectives for the first series of tests were to assess ingress and egress, the usefulness and positioning of translation aids, the layout of the fan-shaped flight deck, and the ability to egress head-first.

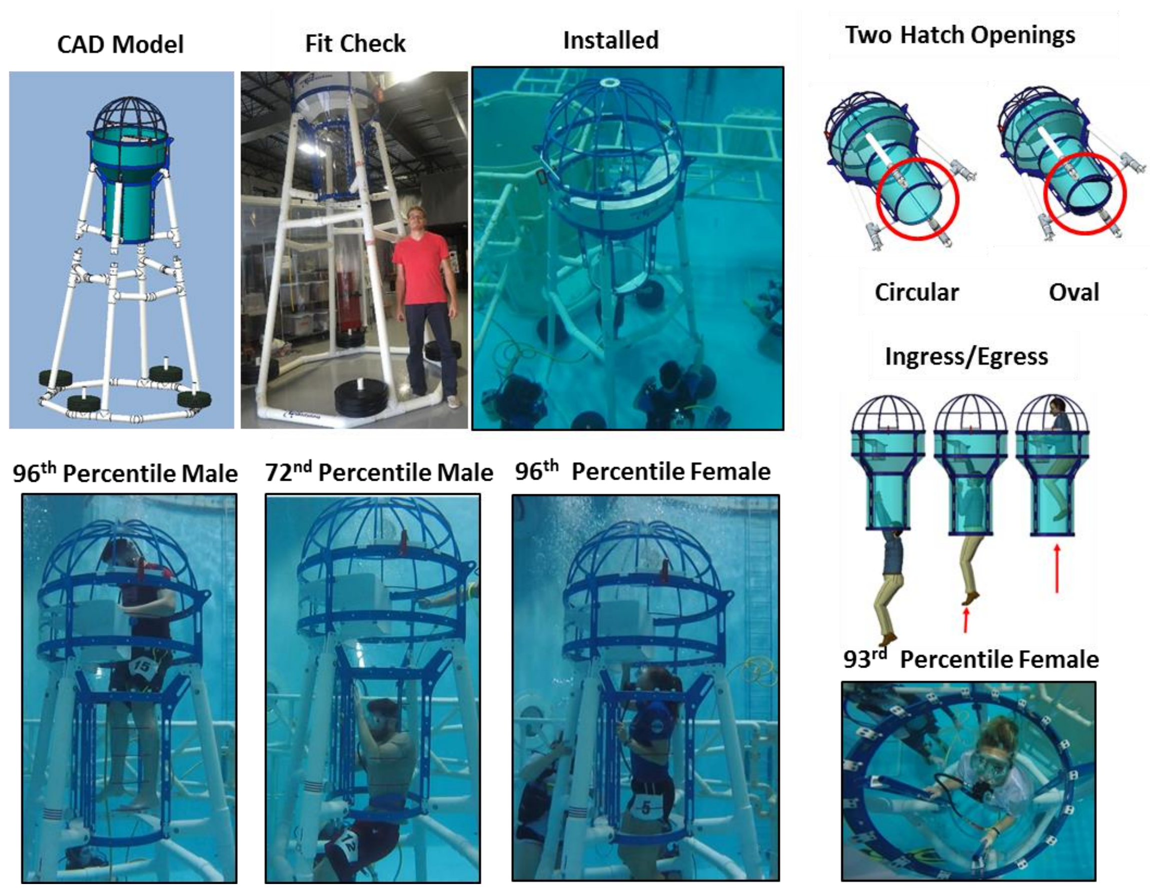


Figure 11. Simulated weightless testing confirms ingress and egress through small hatch openings.

Findings-Test Series 1

- Ingress/Egress (feet first) through the 24" dia. lower torso was possible and unrestricted for all test subjects up to a 98th percentile male (99th percentile was tested in the second series).
- Ingress/Egress (feet first) through the oval (23 in. x 15.5 in.) (0.6 m x 0.4 m) opening was also possible for all test subjects.

- Head first egress through both openings, although not the preferred method, was accomplished by all test subjects who attempted this maneuver. They were able to turn around in the cockpit area and exit the spacecraft head first through the lower torso.
- Hand rails (translation aids) were well positioned with some test subjects suggesting a single hand rail would be sufficient.
- Although foot restraints were not included it was the tendency of test subjects to use an outward pressure of the feet against the lower torso for stability.
- The “cockpit” area, although lacking in some headroom between the test subject and the top of the canopy, was “surprisingly spacious” according to test subject comments.
- Comments and video data showed that the space between the hand rails may be suitable for mounting internal components without interference to translation. This was recommended for further testing.

Ingress/Egress with restrictive service panel, foot restraint, alternative flight deck geometry, and hand controller location

Based on the lessons learned from the first series of tests, the test article was modified to include the volume for subsystem hardware and a servicing panel in the lower torso, a foot restraint, and more mature flight deck concept. Further definition of the air management system added components that were best placed beneath the arms of the pilot as well as in the lower torso area. This lead to the Apache helicopter wrap-around geometry flight deck. Genesis Engineering contracted Design Force to construct the new features for the second series of tests. The new flight deck arrangement allowed more surface area for controls while providing additional volume for equipment packaging (See Figure 12). Testing was needed to evaluate reach, visibility, and restraints for the revised cockpit layout. Based on the results from the first neutral buoyancy test, it was observed the equipment panel positioned between the hand rails represented the least interference to ingress/egress. In addition, because restraints are important for both piloting and operating manipulators concepts were compared, resulting the selection of an adjustable foot restraint placed in the lower torso. Neutral buoyancy testing was required to assess potential translation interference when stowed, adjustability, and effectiveness for controller operation. Before entering the SPS, astronauts pre-position the restraint to their desired height then, once in the cockpit, use a foot-activated lever to swing the restraint into place. The process is reversed for egress. Alternative flight controller concepts and locations were compared by all test subjects. The concepts that were compared were the conventional caged joystick and an unconventional fixed yoke. The caged joystick was

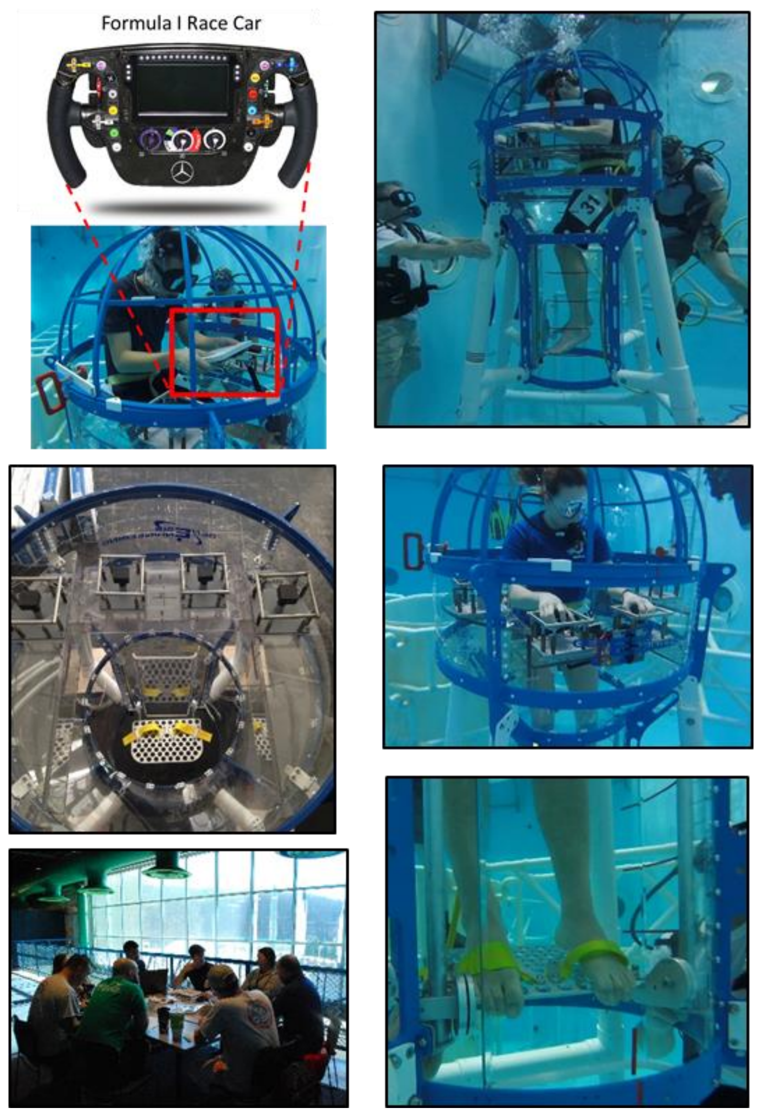


Figure 12. Controller location and foot restraint tests.

modelled off the joystick used to control the ISS Canadarm. The cage is necessary to stabilize the hand during control in zero G. The "fixed yoke" controller was inspired by contemporary Formula 1 race car multi-function steering wheels providing hand stability while allowing finger control.

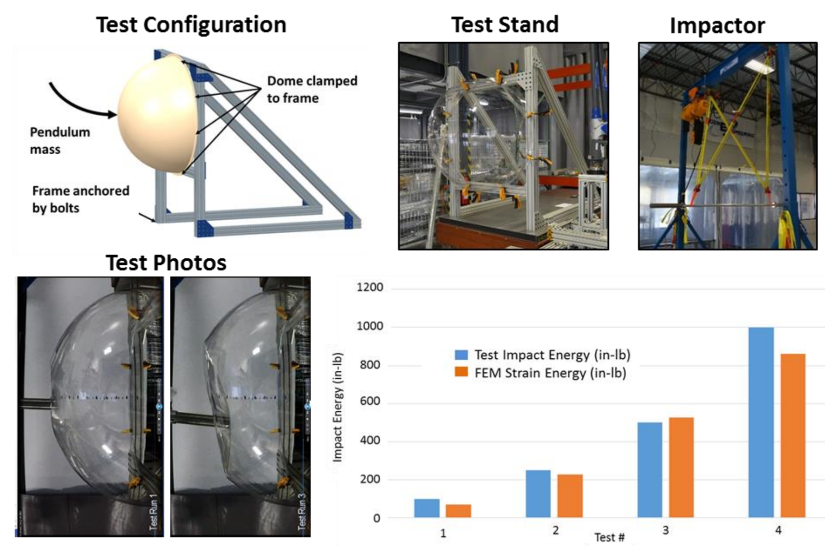
Findings-Test Series 2

- Ingress/Egress through the lower torso with the component closeout was unrestricted for all subjects up to the 99th percentile male.
- Horizontal handrails in flight deck would aid ingress.
- There is adequate working space in the Apache, wrap-around flight deck area for the 99th percentile male.
- Although the foot location played a role, the height of controllers was found to drive the eyepoint for most subjects.
- It is not necessary but favorable to place manipulator controllers angled towards the pilot.
- Joystick controllers at the starboard port side of the flight deck were favored over the "fixed yoke" controller and said to be more intuitive.
- Foot restraints were found effective in stabilizing test subjects; however, the design needs improvement for ease of adjustment and deployment.
- The favored foot restrain angle was downward at 75 degrees from vertical (labeled angle B on the test article).

B. Canopy Impact Testing

A key concern in the design of the dome was its behavior under impact. Should a pilot in the SPS inadvertently fly into the host spacecraft or some other object, the dome must be able to absorb the impact energy while still maintaining its primary functions of containing pressure inside the cabin and providing pilot visibility. Initial analysis was performed using a finite element model to simulate the behavior of the dome under impact. However, effects such as large deflections and yielding produce significant geometric and material nonlinearities in the model, thus a test was desired to verify the accuracy of the model.

For this purpose, an experiment was devised in which a test article was fixed to a stiff support frame in front of a weighted pendulum (Figure 12). Impacts could be achieved by raising the pendulum to a given starting position and allowing it to swing into the dome. By adjusting the mass and starting height of the pendulum, the impact energy could be readily adjusted to meet the test requirements. A total of six different impact tests were performed, with each test doubling the impact energy of the previous test except for test 6, which could not achieve the desired impact energy due to mass and displacement limits of the pendulum.



Test #	Measured Height (in)	Measured Mass (lbs)	Impact Energy (in-lbs)	Deflection (inches)	Yield?
1	1	100	100	2.14"	N
2	2.5	100	250	4.16"	N
3	5	100	500	6.48"	N
4	5	200	1000	8.32"	N
5	10	200	2000	11.22"	Y
6	10	360	3600	12.63"	Y

Figure 13. Impact tests demonstrate SPS dome strength.

The tests were recorded with a high speed video camera, which allowed the maximum deflection of the dome to be measured by analyzing still frames from the footage. The results are summarized in Figure 13. Yielding was first observed in test 5, at an impact energy of 2000 in-lbs. However, at no point in the testing did fracture occur; despite very large strains, no cracks or breaks were observed during the testing. Data collected during the test were then used to correlate the finite element model by applying an enforced displacement to the model that matched the displacement measured during each test. The resulting strain energy was then calculated in the model, which provided a metric that could be compared against the impact energy of the tests. Agreement between the impact energy of the test and the strain energy in the model would indicate accurate model predictions. The model predictions deviated from the test results by an average of 14%, with the largest deviation of 28% occurring during the test with the smallest impact energy, Test 1.

The test yielded valuable insight into how to improve the accuracy of the finite element model as well as the design of the dome itself. The greatest improvement in the accuracy of the model can be had by obtaining more accurate data on the thickness of the dome. The thickness of the test article varied considerably and unpredictably, making it difficult to replicate in the model. If the dome were manufactured with a thickness that was either constant or that at least varied in a predictable way, the stiffness and energy absorption capabilities of the dome could be simulated much more accurately. Obtaining an accurate yield curve for the dome design through stress strain testing would further improve accuracy of the model by eliminating the need to rely on third party data. The large deformations observed during the test also suggest that requirements for the flight article should take this failure mode into account. Rather than simply having a requirement for the dome to not fracture under impact, it may be prudent to add a maximum deflection requirement as well. The deflection requirement would ensure that the pilot would still have room to reach the controls and operate the vehicle in the event of an impact.

X. Subsystems

A. Structures

The SPS structure has been designed for launch loads, retaining cabin atmosphere, inadvertent contact, berthing/docking impact, and micro-meteoroid/debris protection. As described in the configuration section, the major structural elements are the crew enclosure, external equipment bay, and the crown assembly.

The structure of the pressurized crew enclosure includes a hemispheric dome attached to a larger diameter cylinder joined to a smaller diameter cylinder by a cone with a hatch placed at the end of the lower cylinder (Figure 14). Aluminum was chosen because it is an economical, space-rated material while the dome geometry is the lightest solution because of its uniform pressure loading. Polycarbonate was selected for both the pressure canopy and outer unpressurized protective shield because of its excellent strength-to-weight ratio and it is the same material approved for use in EMU helmets. Because of the restricted work space inside the SPS, the internal structure is divided into three major sections; port and starboard crescents with a flight deck bridging the two. This approach was adopted to allow independent assembly and checkout of subsystem components prior to installation. Each section uses an open aluminum framework to provide access for on-orbit servicing. Furthermore, to provide adequate ventilation across all equipment, the closeout panels are made of perforated aluminum sheet metal.

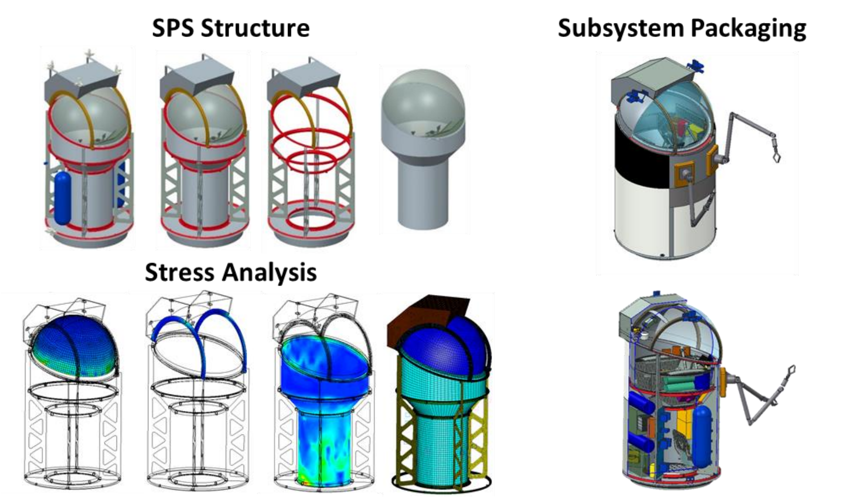


Figure 14. SPS structure has been designed and analyzed.

The external equipment bay is comprised of four vertical longerons that both separate the crew enclosure from the outer Whipple shield and provide surface area for mounting external equipment. A series of circumferential stiffening rings are used to connect the aluminum sandwich panel longerons to the crew enclosure.

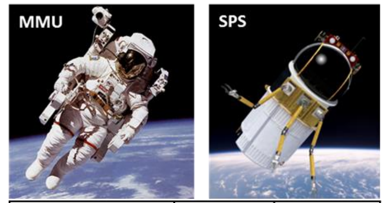
The crown assembly serves to protect the canopy, house avionics, and provide structure for mounting thrusters, lights and cameras. Two versions have been designed; aluminum sandwich panel and monocoque graphite epoxy.

Additional structure includes two aluminum "golden arches" that extend over canopy providing bump protection and function as a guide path for three sets of visors.

B. Propulsion

The SPS uses the same cold gas propulsion system as the flight proven, human-rated Manned Maneuvering Unit (MMU) see figure 15. This system stresses reliability, safety, and ease of use yet is quite capable as demonstrated on STS-51-A with the retrieval of two large communication satellites. The propellant is compressed nitrogen which is neither a toxic nor combustible, and is easily refilled on orbit using existing space-rated pumps. The GN_2 propellant is stored at 3000 psi in two commercially available tanks then stepped down to the thruster valve operating pressure through regulators downstream of cutoff valves. The system is comprised of identical halves, each fueled by one of the two tanks on the SPS. The halves are functionally symmetric: when the system is functioning, both systems will expend the same amount of fuel. If a tank or pressure regulator fails, the spacecraft can be fully controlled by a single half of the propulsion system. Like the MMU, the SPS includes an attitude hold capability enabling the position to be held without having to use the hand controllers.

A unique SPS safety feature that is being explored takes advantage of the emergency Nitrogen-Oxygen (Nitrox) repressurization gas as propellant. If there is a breach in the crew enclosure, two nitrox tanks are used to feed-the-leak. However, if there is no breach and the emergency calls for more propellant, valves can be opened allowing the Nitrox to be used as get home propellant.



	MMU	SPS
Delta V (m/s)	13.7*	12.3**
Nom. Range (m)	137	same
Operation (hr)	6	same
Propellant	GN2	same
Prop mass (kg)	5.9	10.4
No. Thrusters	24	same
Thrust (N)	7.56	same
Tank Press (kpa)	20,684	same

* m/s useful delta v
** At 550 kg mass

Figure 15. MMU and SPS propulsion Comparison.

C. Air Management

Genesis Engineering has partnered with Paragon Space Development Corporation in developing the SPS Air Management System (AMS) see figure 16. SPS excursions are less than 8 hours thus only an AMS versus a complete Environmental Control Life Support System (ECLSS), is required. The cabin is designed for earth-like, sea-level (14.7 psi, 80% N2, 20% O2) atmosphere, eliminating the need for the standard EVA pre-breathe without the risk of decompression sickness (the bends).

The progress that has been made in defining the SPS AMS includes creating a functional schematic, sizing components, and packaging them within the SPS. Below is a description of the SPS AMS sub-assemblies:

Air Revitalization System

The Air Revitalization System (ARS) is the core of the AMS providing overall ventilation, CO2 removal, humidity control, trace contaminant control, and heat removal. Unlike the strenuous workout associated with suited EVA, operating the SPS is be more like flying a commercial aircraft thus there is no need for the liquid cooling ventilation garment. With a reduced metabolic load, there is less crew-produced water vapor, but, as a precaution, the initial flights include an oral-nasal mask that guides respired water and CO2 directly to the ARS. This approach significantly reduces cabin air humidity and CO2 levels and increases the removal efficiency of these metabolic contaminants. Ventilation originates at a spray bar located at the base of the canopy with the flow washing the dome like an automobile defroster. Cool, dry purified air moves up the canopy over the pilot's head collecting any cabin CO2 and water vapor then down to an inlet filter located in the lower torso for convenient servicing. After the filter, air passes through replaceable potassium superoxide cartridges for CO2 removal and O2 supply, then through a trace contaminant and humidity control unit which includes a non-condensing heat exchanger, and finally back out into the cabin. Successive iterations of ARS packaging have both reduced the equipment volume and improved access for on-orbit servicing.

Thermal Control System

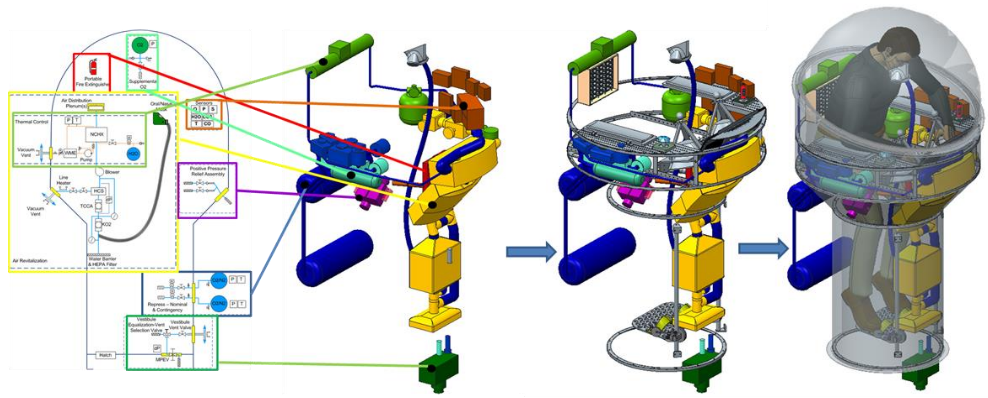
The SPS Thermal Control System regulates the internal cabin air temperature. The air flow is designed to collect crew and equipment heat passing through the ARS non-condensing heat exchanger to condition the cabin to a design set point of 70 degrees F, however this is controllable by the crew member. A water membrane evaporator, like the one currently in development for NASA's next space suit, takes water from the heat exchanger, cools it by evaporating a portion to space vacuum and sends a majority of the cooled water back in a loop to the heat exchanger. A manual bypass valve is used by the crew member to regulate cabin temperature for comfort.

Supplemental Oxygen

The Supplemental Oxygen system acts in both an additive mode as well as an emergency O2 supply. If the cabin O2 level is low, a valve is opened to release oxygen into the cabin at a low rate. Although improbably, if the air revitalization system fails catastrophically 7 hours of contingency oxygen provides more than enough time for the pilot to return to the host spacecraft.

Repress Nitrox

Rapid depressurization is an important concern for any spacecraft. If the SPS experiences a leak, the Re-pressurizing Nitrox system (75% N2/25%O2) will activate, allowing air into the cockpit to maintain pressure and support life. Use of Nitrox as opposed to separate N2 and O2 supplies greatly simplifies operations during a stressful and dangerous failure scenario and therefore increases safety. The system is sized to provide 30 minutes of breathable air with a 0.25 in. (6.35 mm) diameter sized hole.



	Max	Min
Source	W	W
AMS	265	50
Other Electronic	150	50
Crew	100	100
Spacecraft body	0	0
Spacecraft Dome	500	250
Total	1015	450
water (kg/hr)	1.6	0.7
water (8 hr)	13.1	5.9
~Dry mass (kg)	4.6	2.3
Wet mass (8hr, kg)	17.7	8.2

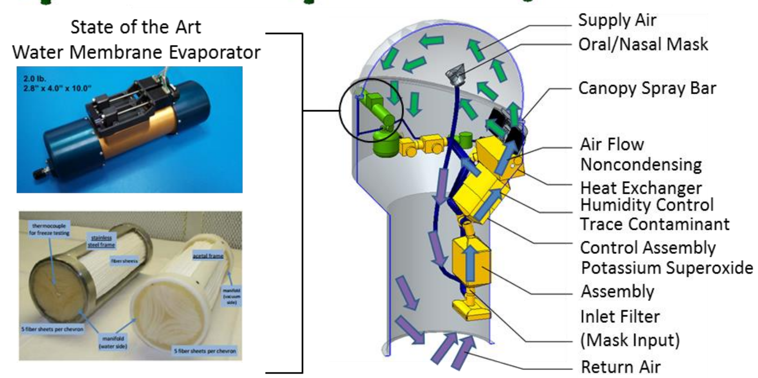


Figure 16. The SPS Air Management System operates with an earth-like sea-level cabin atmosphere.

Instrumentation

During flight, it is important to know the status of the environment in order to determine and check overall flight safety. The Instrumentation system is essentially all of the sensors and gauges that output for display of cabin air pressure, cabin air temperature, CO2, O2, CO and humidity. Instrumentation also provides tank pressure and temperatures for all stored gasses.

Positive Pressure Control

The positive pressure control system prevents over pressurization within the enclosure.

Fire Detection and Suppression

Because the SPS has the same atmospheric gas composition as the ISS, the risk of fire is less than a pure oxygen space suit. Regardless, the SPS is equipped with a hand held water mist fire extinguisher which allows fire suppression without contaminating the air within the cabin. Carbon Monoxide, a primary combustion product released during spacecraft fires, is continuously monitored. Upon detection, an alarm sounds, and the cabin ventilation is stopped, unless manually overridden by the crew.

D. Electrical Power

The SPS Electrical System (Figure 17) is powered by 2 Lithium ion 100 Amp hour batteries designed to operate for an 8 hour mission per battery. The power distribution contains 2 parallel interface connectors providing primary

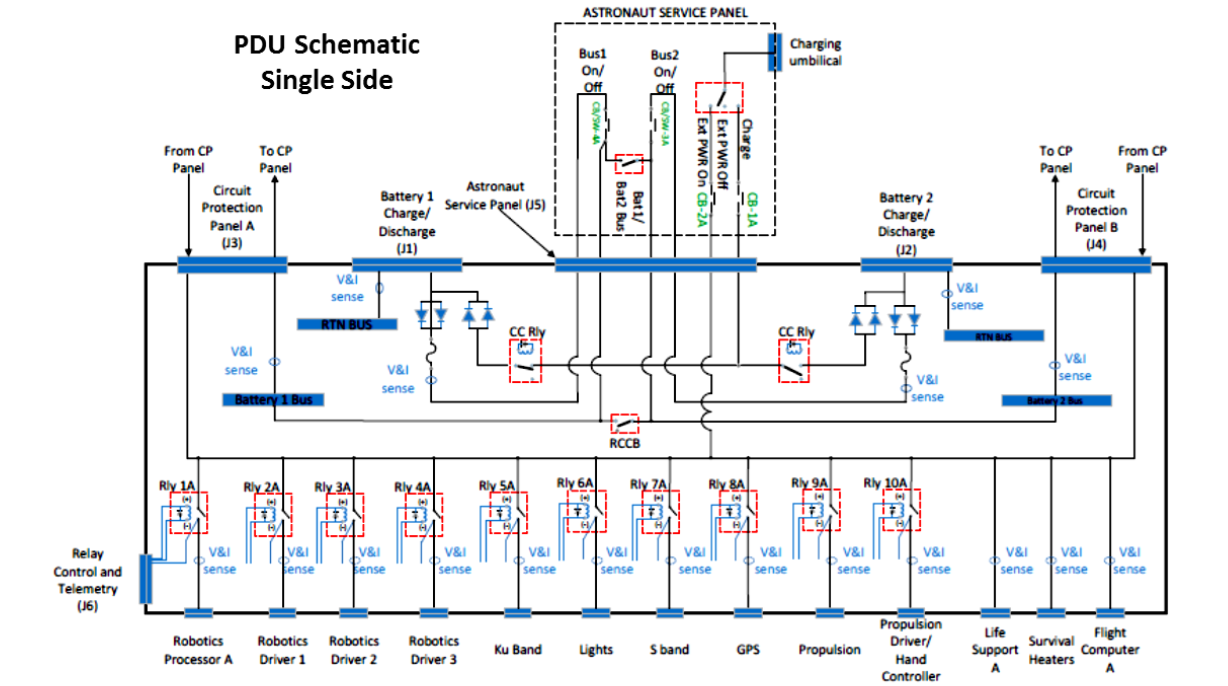


Figure 17. SPS electrical power system based on flight-proven hardware

and redundant paths for all loads. The Power Distribution Unit (PDU) is fully cross strapped so that either battery can power any primary or redundant load. Load switching is done by high reliability, space qualified relays controlled by the main computer. Relay position and load currents are monitored and reported as part of the PDU housekeeping telemetry. The PDU interfaces not only with each battery and all loads but also a Circuit Protection Panel and Astronaut Service Panel

Wiring and current protection are sized to each particular load. The Astronaut Service Panel is used to provide an internal accessible panel for charging, controlling external power or switching battery busses. Diodes and switches are used to isolate internal and external power as well as charging operations. The Circuit Protection Panel provides the astronaut with a visible indication of circuit status including a current over load or "tripped" state.

E. Avionics

At the heart of the Single Person Spacecraft is the Genesis Engineering Solution's GEN6000 data processing system. GEN6000 offers both speed and versatility. The system can step outside of typical roles such as Command and Data Handing, and Guidance and Navigation Control, and take on more computationally demanding tasks such as image processing.

The GEN6000 processing system is a derivative of Spacecube 2.0, developed by NASA Goddard Space Flight Center (GSFC). Spacecube was born out of a need for a computation system that was both powerful and reconfigurable. Spacecube offers an all in one platform that can accomplish all of the computing needs of a spacecraft, rather than simply providing flight control. The flexibility and computing power offered allows many tasks that were limited to ground operations, to be performed in flight.

On the Single Person Spacecraft, GEN6000 will be employed to accomplish flight control, robotics operation and processing relevant to the Air Management System. GEN6000 is a product of Genesis Engineering Solutions, and the flight article will be assembled in house.

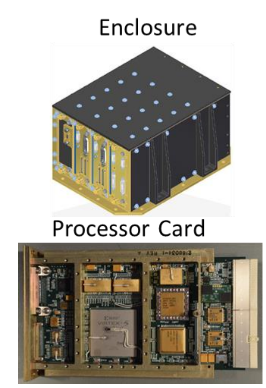


Figure 18. SPS Data Processing.

F. MMOD and Radiation Protection

Spacecraft offer better protection than space suits. For LEO operations, the SPS Whipple shield coupled with MLI attenuates the impact energy from debris and micrometeoroids. This solution is designed for the LEO environment and therefore assumed acceptable for Beyond Earth Orbit (BEO) operations without a debris hazards. No additional radiation protection is required for LEO but for BEO, two layers of protection are available (Figure 19). A polyethylene outer layer is used to surround the SPS with the second layer provided by a wearable radiation jacket like the one proposed by ILC.

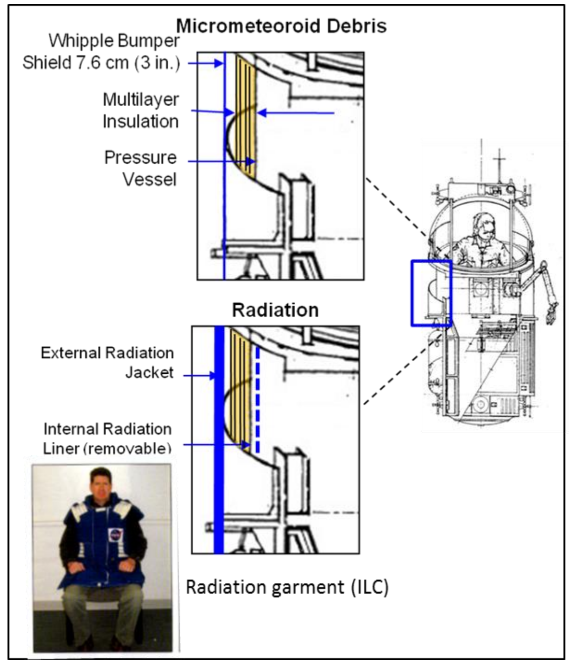


Figure 19. Two layers of radiation protection.

XI. Summary

The SPS is further developed than any preceding concept. The overall configuration has been established, the mass properties along with growth allowances are being managed, the structure has been designed, the air management system is defined and packaged, key dimensions have been verified through neutral buoyancy testing, and a flight simulator is being used to assess the performance of the propulsion system. These accomplishments represent a significant investment of private resources aimed at providing a new capability for the next generation of human spaceflight. This new capability is the timely and logical solution for safe and efficient external operations for the Gateway habitat, Mars transit vehicle, satellite servicing, and Phobos exploration. Flight testing is nearer because of the head start provided by this early SPS development.

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10. Robert Stewart, former MMU astronaut, for concept review and comments.

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