COMMERCIAL SPACEWALKING: DESIGNING AN EVA QUALIFICATION PROGRAM FOR SPACE TOURISM

Matthew A. Gast
United Space Alliance, LLC
600 Gemini, Houston TX, 77058-2783 ; USA
matthew.gast-1@nasa.gov

ABSTRACT

In the near future, accessibility to space will be opened to anyone with the means and the desire to experience the weightlessness of microgravity, and to look out upon both the curvature of the Earth and the blackness of space, from the protected, shirt-sleeved environment of a commercial spacecraft. Initial forays will be short-duration, suborbital flights, but the experience and expertise of half a century of spaceflight will soon produce commercial vehicles capable of achieving low-Earth orbit. Even with the commercial space industry still in its infancy, and manned orbital flight a number of years away, little doubt exists that there will one day be a feasible and viable market for those courageous enough to venture outside the vehicle wearing nothing but a spacesuit, with nothing but preflight training to rely upon. What that Extravehicular Activity (EVA) preflight training entails, however, has yet to be defined. While a number of significant factors will influence the composition of a commercial EVA training program, a fundamental question remains: "what minimum training standards must be met to ensure a safe and successful commercial spacewalk?" Utilizing the experience gained through NASA's Skills program – designed to qualify NASA and International Partner astronauts for EVA aboard the Space Shuttle and International Space Station – this paper identifies the attributes and training objectives essential to the safe conduct of an EVA, and attempts to conceptually design a comprehensive training methodology meant to represent an acceptable qualification standard.

1. Introduction

A viable commercial space industry is emerging as the 21st century heads into its second decade, and it is reasonable to assume that private companies will possess the capability to carry adventuresome individuals into low-Earth orbit (LEO) before this decade is out. Already companies are constructing and flight-testing vehicles to meet market demands, be they suborbital manned flights, or unmanned cargo flights to the International Space Station (ISS).

As these capabilities take shape and entrepreneurial aspirations come to fruition, the boundaries of what is possible will be tested. It is easy to envision those first paying passengers to low-Earth orbit returning to Earth and exclaiming that the experience was well worth the price. History has shown, however, that there will be some who are not content with the current state of affairs and seek to push the envelope. In commercial spaceflight, the most prominent boundary yet to be discussed at length, spacewalking (also known as an extravehicular activity, or EVA), is the one that many will quickly try to cross once ready access to low-Earth orbit is achieved. The reason for the need to cross that boundary can be found in the very basis of human nature.

In 1620, the Saints and Strangers aboard the *Mayflower* arrived in the New World from the Old, at a place they called Plymouth. Fact and myth regarding the landing, and the famed Plymouth Rock, became intertwined over the subsequent centuries, but still, in the American psyche, there is an attachment to Plymouth Rock itself as the place where these pilgrims first stepped foot into the New World [16].

Three hundred forty nine years later, another first step would resonate through the souls of not just the Americans who witnessed it, but through those of an entire race. On July 20, 1969, six and a half hours after *Eagle* had landed, Apollo astronaut Neil Armstrong descended the ladder of the Lunar Module (LM) and stepped onto the surface of the Moon, declaring "this is one small step for man, one giant leap for mankind."

As the first person to step foot onto the Moon, Armstrong's excursion from the LM was certainly the most historic spacewalk, but it was not the first. That honor belongs to cosmonaut Alexei Leonov. On March 18, 1965, in low-

Earth orbit aboard the Soviet spacecraft *Voskhod 2*, Leonov, garbed in the first spacesuit designed for extravehicular activity (EVA), ventured into the vacuum of space for twelve minutes and nine seconds.

Just three months later, on June 5, 1965, Gemini astronaut Ed White became the first American to conduct an EVA, spending nearly 22 minutes outside the Gemini 4 spacecraft. Enthralled with the spacewalking experience, White remained outside beyond the planned time, and was eventually ordered back inside by NASA's Mission Control Center. As he was ingressing the spacecraft at the completion of the EVA, White declared that "this is the saddest moment of my life [9]."

Exploration, be it across the ocean or across space, relies on science and engineering to create the hardware needed for safe passage. Yet, in a primordial sense, the experience of exploration takes on a new aura when the explorer is able to move independent of his ship. Standing on the deck of the *Mayflower*, staring at the shore, does not possess the same aura as stepping foot into the New World. That physical connection with the surrounding environment humanizes exploration; the independence personalizes it.

It was that severing of his personal connection with the environment he was exploring that caused Ed White to feel so saddened, just as it was that personal, human connection to the surface of the Moon that made Armstrong's first step so important to humanity. And it is that same need for a personal connection that will someday fuel an entire industry catering to those yearning to become spacewalkers.

2. Scope and Purpose

NASA has spent years evolving an EVA training program that focuses on developing the necessary skills that astronauts need to safely and successfully conduct highly complex spacewalks. NASA's highly-trained, EVA-qualified astronauts possess the capabilities to perform such demanding tasks as Hubble Space Telescope repair, and International Space Station (ISS) construction. Those training standards, however, are not applicable to the vast majority of commercial spacewalkers, as this paper will later show.

This paper will, however, attempt to employ many of the lessons learned from that evolutionary program to lay out a set of guidelines that outline acceptable spacewalking qualification standards for commercial astronauts. Please note, however, that this paper represents merely a first draft, and although it tries to comprehensively capture the necessary training objectives, any failure or oversight is the fault of the author's alone.

Spaceflight is akin to a transatlantic crossing by ship. The ship becomes home, the views of the distant horizon are breathtaking – even in their repetitiveness – and the rise and set of the sun is awe-inspiring. Spacewalking, on the other hand, is analogous to SCUBA diving. For some, the personal connection made with the sea through SCUBA diving expands the experience. The diving industry, in fact, has grown so significant that, in many cases, the ship has simply become a vessel to facilitate the diving experience.

The maturity of this industry, made up of categories like recreational, technical, scientific, and commercial diving, has resulted in the development of certification standards for the various levels of capability. These training standards – ranging from the self-regulated recreational diving community to the government-regulated commercial diving trade – provide continuity to a global business that employs thousands of companies, ensuring any individual diver's abilities meet industry-accepted minimum qualifications.

Spacewalking, on the other hand, has only three government agencies across the world that possess this unique capability: the National Aeronautics and Space Administration (NASA), the Russian Space Agency (RSA), and the Chinese National Space Agency (CNSA). This exclusivity has allowed these agencies to develop and maintain specialized "in-house" training programs. For example, NASA astronauts qualified for EVA in the American spacesuit, the extravehicular mobility unit (EMU), are not automatically qualified to conduct an EVA in the Russian Orlan spacesuit. Instead, a NASA astronaut scheduled to conduct an EVA aboard the ISS in the Russian Orlan spacesuit must travel to the Gagarin Cosmonaut Training Center (GCTC) in Star City, Russia, and undergo a training program specific to the Orlan itself before being deemed qualified.

The emergence of a commercial spaceflight industry will mean the emergence of a commercial spacewalking industry. It may well be that such government agencies as the Federal Aviation Administration (FAA) and the Occupational Safety and Health Administration (OSHA) will dictate rigorous standards for all commercial spacewalkers. This paper, however, will first categorize spacewalking capabilities, to delineate necessary certification levels – particularly with regard to which may suffice with self-regulation rather than the much more restrictive government regulations – and then focus on the minimum certification requirements for what would be considered an entry-level spacewalking qualification.

3. Spacewalk Categorization

It is necessary to categorize spacewalking capabilities to differentiate the roles, responsibilities, and thus the minimum certification requirements, of the various types of commercial spacewalkers. To do this, an analog comparison will be made with the diving industry, and in doing so, three separate, distinct categories of spacewalk certification can be identified.

To clearly distinguish the capabilities of each category, the naming convention will mimic that used by the United States Navy to classify Navy Divers [17]:

- Spacewalker, 2nd Class – The basic certification level, awarded upon completion of a training program that meets or exceeds the standards set for entry-level certification

- Spacewalker, 1st Class – The advanced certification level, awarded upon completion of a training program that meets or exceeds the standards set for advanced certification

- Master Spacewalker – The highest certification level, awarded to a Spacewalker, 1st Class, upon completion of a training program that meets or exceeds the standards for professional certification

3.1 Spacewalker, 2nd Class

This is the first certification in a spacewalk training program, and can most easily be thought of as meeting the minimum qualifications to safely perform a *non-complex* EVA in low-Earth orbit, under supervision. This certification would be, in many respects, similar to that of a recreational SCUBA diver. Due to the fact that most of the commercial astronauts paying for a flight to space, at least in the beginning of commercial spaceflight, will be rookies, this certification level will be the most populous, with the vast majority of commercial spacewalkers never surpassing this certification.

Because the majority of commercial spacewalkers will perform an EVA only once (or repeatedly on a single spaceflight), the level of training, and the associated regulations, must be limited to just the necessities, to ensure a viable marketplace. Excessive regulations lead to excessively expensive training programs, when the preponderance of commercial spacewalks will be relatively simple.

There is a considerable risk in any extravehicular activity, but with respect to EVA, the terms *non-complex* and *complex* refer to the level and difficulty of the activities performed by the spacewalking astronauts. Here, *non-complex* implies few tasks that require tool operations or the assembly of hardware within the vacuum of space. To illustrate the notion of *non-complex* EVA tasks, the following sample timeline is presented in Table 1. As it is, for many second-class spacewalkers, this could well represent the extent of desired activities.

Spacewalker, 2nd Class – EVA Timeline	
Task	**Duration (hh:mm)**
Airlock Egress	00:30
Translation to view-points	00:45
Observation and photography of Earth	02:00
Photography of spacewalker(s)	00:45
Airlock Ingress	00:30
Total Time EVA	04:30

Table 1 – Sample: Spacewalker, 2nd Class EVA timeline

The simplicity of the above list of tasks highlights the danger in over-regulation. Since a large percentage of commercial astronauts will primarily want to perform an EVA to make that personal connection with the surrounding environment – to translate under one's own power around the vehicle's exterior, to view the Earth not through a window but through a very thin helmet visor, and to take pictures – the level of training necessary will be relatively basic. Furthermore, until costs drop dramatically, the vast majority of commercial astronauts will fly to space a single time. As such, the training program must cater to this constituency, to ease access to this profoundly human need to connect with one's surroundings.

This is not unlike a recreational SCUBA diving certification. The limitations set upon recreational divers allows the diving industry to self-regulate certification standards, avoiding government regulations and the added expenses that those regulations impose onto a training program. Recreational divers do not want to learn to weld underwater; they simply want to have the skills needed to explore the oceans, lakes and rivers of the world. The same will likely be said of the greater part of the commercial spacewalking community.

While recreational diving is not government regulated, that is not to say that it does not have training standards. Under self-regulated guidelines, internationally recognized agencies like the National Association of Underwater Instructors (NAUI) and the Professional Association of Diving Instructors (PADI) have developed and implemented certification programs that meet or exceed the standards proposed by the American National Standards Institute (ANSI). ANSI Standard Z86.3-1989 documents the recommended the entry-level scuba certification – minimum course content for underwater safety [3]. The scope of this document is encapsulated in its opening:

> *This standard provides minimum course content requirements for entry-level instruction in recreational diving with scuba (self-contained underwater breathing apparatus). However, these requirements should under no conditions be considered to define a level of optimum training in the use of scuba. Instructional programs that extend beyond these requirements should, in fact, be encouraged. The requirements of this standard are meant to be comprehensive, but general in nature. That is, the standard presents all the subject areas essential for minimum scuba training in recreational diving, but it does not give a detailed listing of the skills and information encompassed by each area.*

Replacing the word *scuba* with *spacewalk* would provide a thorough explanation of a practical standard for Spacewalker, 2nd Class training. It is expected that competition in commercial spaceflight will yield considerable differences in hardware such as spacecraft airlocks and commercial spacesuits themselves. A standard must be broad enough to provide training guidelines that are independent of hardware operations and constraints. For example, there would be notable differences in the training programs for two spacewalking companies if one used an umbilical to connect the spacesuit life support system directly to the vehicle's life support system (similar to NASA's Gemini program), while another company used a self-contained life support system in a backpack attached to the spacesuit (similar to NASA's current spacesuit). As such, the standards have to allow each company to develop its own training program while adhering to said standards.

By allowing the industry to regulate itself with respect to Spacewalker, 2nd Class certification, commercial companies could minimize costs by developing training programs that provide the skills necessary for clients based on the complexity of the activities those clients could expect to participate in during an EVA. As such, the actual minimum requisite training time that comprises a specific training program would be determined by the service provider in accordance with the required course content.

Finally, the minimization of training (and thus the minimization of cost to the prospective customer) necessitates agreement that someone holding the certification of Spacewalker, 2nd Class not be allowed to perform an EVA in low-Earth orbit without the direct supervision of a Master Spacewalker. This is where Spacewalker, 2nd Class, differs drastically from a recreational diver. The risks associated with extravehicular activities cannot be overemphasized, and as such, direct supervision by a Master Spacewalker ensures that the dangers – such as spacesuit malfunctions, micrometeoroid strikes, decompression sickness, tether entanglements, and loss of physical contact with the spacecraft, to name a few – are minimized. Emergencies in the vacuum of space can quickly result in death, but an experienced spacewalker can often facilitate the actions necessary to protect the safety of the other crewmembers.

3.2 Spacewalker,1st Class

This is the second certification in a spacewalk training program, and can most easily be thought of as meeting the minimum qualifications to safely perform an EVA in low-Earth orbit without the supervision of a Master Spacewalker. Analogously, this certification would be similar to that of a technical or scientific diver.

The technical and scientific diving communities possess additional , task-specific training beyond the recreational diver certification, but are likewise still self-regulated. Technical diving – with specialized disciplines ranging from cavern and cave diving, to decompression diving, to wreck penetration diving – are still under the auspices of organizations like NAUI and PADI.

Similarly, scientific diving was made exempt from OSHA's commercial diving regulations in 1982, provided the scientific diving community meet certain conditions [1]. Since that time, OSHA has recognized the American Academy of Underwater Sciences (AAUS) as the standard-setting organization for the scientific diving community.

One of the conditions to the scientific diving community's exemption can, in a way, be applied to spacewalking to provide greater flexibility in training programs and the types of services that commercial spaceflight companies can offer their customers. The guideline from OSHA to the AAUS is as follows:

> *The tasks of a scientific diver are those of an observer and data gatherer. Construction and trouble-shooting tasks traditionally associated with commercial diving are not included within scientific diving.*

Adopting a similar policy within the spacewalking standards would provide flexibility.

In the diving community, gaining advanced certifications requires the type of experience that can only be gained through diving. For example, to become certified in the technical discipline of ice diving through NAUI, a candidate must hold an advanced scuba certification, and have a minimum of 50 logged dives in a variety of conditions [12]. In the world of commercial spacewalking, where access to low-Earth orbit –, when it becomes available – will cost in the millions of dollars, experience will be difficult to attain. Therefore, Spacewalker, 1st Class certification should be available via more than one method.

Two separate training programs could be envisioned that would lead to Spacewalker, 1st Class certification. One program would utilize a stepping-stone approach. By first gaining 2nd Class certification, one could first perform an EVA in low-Earth orbit under Master Spacewalker supervision, as previously described. Then, should a customer return to an EVA training program in preparation for a second spaceflight, the training flow would incorporate the experience gained in low-Earth orbit to supplement course content. The Spacewalker, 1st Class, training program would take EVA duration, performance and aptitude into account, designing a training flow that reflects the individual's capabilities.

This program would appeal to customers who do not expect to fly in space a second time, or are unsure whether the added time and costs to attain Spacewalker, 1st Class certification are justifiable.

A second, accelerated program would cater to customers who possess the capacity and the desire to undergo the advanced training essential for this certification (and are thus willing to pay more for said training). While EVA comes with considerable risk, it can be minimized through training. By not requiring spacewalkers at this certification level to be supervised by a Master Spacewalker, this parallel method would provide flexibility to both commercial operators and the customers.

This type of training program would not have the luxury of relying on previous on-orbit experience to augment the flow. Instead, this flow would rely on much more classroom and neutral-buoyancy training to develop the skills needed to perform an unsupervised EVA.

Since there is no direct supervision, this certification should focus heavily on emergency response; a Spacewalker, 1st Class must be capable of addressing and efficiently resolving any spacesuit, vehicle or spacewalking partner emergency, thus minimizing the risks to crew and vehicle safety.

This diversity in Spacewalker, 1st Class training programs, along with the recognition that flight experience has considerable value, provides significant flexibility to commercial spacewalking service providers, allowing them to cater to the customers' desires without compromising the training standards that such an endeavor demands.

3.3 Master Spacewalker

This is the highest certification in a spacewalk training program, and can be thought of as meeting the minimum qualifications to safely perform a *complex* EVA in low-Earth orbit. Analogously, this certification would be similar to that of both a commercial diver and a divemaster/instructor.

This certification would allow the holder to act in a variety of capacities in low-Earth orbit. As previously stated, a Master Spacewalker could act as a "guide," leading *non-complex* spacewalks for Spacewalker, 2nd Class customers. In this capacity, the training standards would ensure that the Master Spacewalker could effectively respond to any and all emergencies, without the assistance of any spacewalker under his supervision. Much like a divemaster, a Master Spacewalker would be responsible for the safety of those under his guidance.

Additionally, a Master Spacewalker could act in a construction capacity, similar to a commercial diver. The commercial spaceflight industry will open the doors to many entrepreneurial possibilities in low-Earth orbit. Space hotels, privately-owned orbiting laboratories, and satellite maintenance are but a few of the possible industrial endeavors of the future, and like the commercial diver industry, construction and maintenance of those types of facilities will require personnel with the training and abilities to complete complex tasks in low-Earth orbit in a timely and cost-effective manner.

The training a NASA astronaut undergoes in preparation for a flight aboard the space shuttle or International Space Station would equate to Master Spacewalker certification. The complexity of the tasks requires a mixture of not only technical skills, such as:

- Translation
- Tool operations
- Body restraint operations (including foot restraints)
- Hardware replacement
- Airlock hatch, egress and ingress operations

but also attributes that could be considered "soft skills," such as:

- Situational awareness
- Spatial awareness
- Adaptability
- Teamwork
- Communications (between EVA partners, and also with ground controllers)
- Work efficiency

NASA's spacesuit, the extravehicular mobility unit (EMU) may be more complicated than future spacesuits that can incorporate more automation and computing power, and the complexity of the assembly of the ISS demands extensive training, but as a benchmark for commercial spacewalking training programs, NASA may spend on the order of 500 hours to train an astronaut for his first spacewalk [10]. And even with that much training, whenever possible, NASA prefers to assign a rookie spacewalker with a veteran for the rookie's first spacewalk, to ensure that the rookie spacewalker has someone with experience to provide guidance.

With respect to self-regulation versus government-regulation, the Master Spacewalker certification (and subsequent operations in low-Earth orbit) will likely come under the purview of government regulations. Due to the nature of the work done by the commercial diving industry, it is regulated by such federal agencies as OSHA[14] and the United States Coast Guard (USCG), with training and operational standards set by ANSI, the Association of Commercial Diver Educators (ACDE)[4] and the Association of Commercial Diving Contractors International (ADCI)[2]. The construction of a space hotel, or the repair of a satellite in low-Earth orbit, will likely place a Master Spacewalker at even greater risk, as a spacewalker working in such a capacity may be required to interface with, for example, electrical systems, fluid coolant systems, mechanical devices and tools. Because of this, it is not difficult to envision that the standards for Master Spacewalker training and operations could fall under government regulation. Whether those regulations would come from OSHA, the Federal Aviation Administration (FAA) or some not-yet-created Federal Space Administration (an agency responsible for all operations above an altitude of, say, 100 kilometers, the internationally recognized definition of space) will need to be determined [7].

Finally, the regulations within this certification level should provide some degree of flexibility to apply on-orbit experience toward this certification, much like that proposed above for the Spacewalker, 1st Class certification. It is not difficult to imagine a day when spacewalking will be a profession like that of a commercial diver, or an airline pilot, and the certification process should not unnecessarily hinder the growth of an emerging industry.

3.4 Spacewalker Categorization – A Final Word

The above represents one way in which the categories (and associated responsibilities) of spacewalk certification could be delineated. Each requires detailed standards, much like those provided by ANSI for entry-level and commercial divers, to provide guidance to companies designing spacewalk training programs to meet market demand [3][4]. The remainder of this paper will focus on an outline for entry-level spacewalking certification standards. Due to its concise, effective content and layout, this standards outline will follow a format similar to the ANSI standard for entry-level scuba certification [3]. By doing so, this paper hopes to give some understanding of the level of commitment a company would need to make to develop and implement a training program (with the associated facilities) that could take those with no EVA knowledge and qualify them to perform an EVA in low-Earth orbit as a Spacewalker, 2nd Class.

4. Eligibility for Certification: Spacewalker, 2nd Class

Due to the risks associated with spaceflight in general, and EVA specifically, an individual should meet the following minimum prerequisites:

(1) *Age.* An individual be at least 18 years of age, with no upper limit for certification.

(2) *Scuba Certification.* EVA training requires the use of a neutral-buoyancy facility (i.e. water tank); an individual must possess an entry-level scuba certification card (often referred to as a C-card) prior to beginning EVA training.

(3) *Medical Certification.* Due to the rigors of EVA training and spaceflight, an individual must obtain medical certification prior to beginning EVA training. While no civilian medical certification currently exists that directly addresses spacewalking, an initial supplementary standard could be the “Diving Medical Exam” from the American Academy of Underwater Sciences (AAUS) [1], taken from the seminal work in the field of diving medicine by Dr. Alfred Bove [5][6].

(4) *Knowledge.* An individual must take and pass a written examination on spacewalking. The examination tests entry-level knowledge of the following content, to be presented in the training program:

   a. General guidelines
   b. Space environment
   c. Spacesuit equipment
   d. Spacesuit emergencies
   e. Spacesuit malfunctions
   f. Medical problems associated with spacewalking
   g. EVA preparation
   h. EVA operations
   i. EVA emergencies
   j. Neutral-buoyancy training
   k. Vacuum chamber training

(5) *EVA Skills.* An individual must successfully demonstrate, to a Master Spacewalker acting in an evaluative role, the EVA skills necessary to perform a spacewalk in low-Earth orbit. This demonstration must take place in a neutral-buoyancy facility, and must exceed the duration of the scheduled low-Earth orbit spacewalk. By adhering to this time requirement, a Master Spacewalker can ensure that an individual possesses the physical and mental ability to safely function as a Spacewalker, 2nd Class, for the full duration of an actual spacewalk.

5. Minimum Course Content: Spacewalker, 2nd Class

The following information is presented to act as a guideline for the type of material necessary to ensure an individual possesses all the information required to safely and successfully perform an EVA in low-Earth orbit in the capacity of a Spacewalker, 2nd Class. The newness of this industry will result in drastic differences in spacesuit design, on-orbit vehicle capabilities (the use of an airlock, similar to the space shuttle and ISS, versus a spacecraft designed to take the entire pressurized volume to vacuum, similar to the Gemini and Apollo spacecraft), and the level of experience each commercial spaceflight company can offer individual spacewalkers (such as EVA duration and the number of simultaneous spacewalkers, for example). This will result in potentially vast differences in available EVA training programs.

5a. General Guidelines

This subsection addresses general guidelines that equate to EVA best practices. Adhering to these best practices help limit the risk associated with EVA. A training program should identify and explain the importance of these best practices.

- EVA planning
  - EVA overview
  - EVA training overview
  - Applicable spaceflight rules and regulations
  - Spaceflight company-specific EVA options
- EVA team complement
  - Minimum of two spacewalkers at all times
- Master Spacewalker roles and responsibilities
- Spacewalker, 2nd Class roles and responsibilities

5b. Space Environment

This subsection addresses the space environment to familiarize an individual with the physical conditions that are experienced during an EVA.

- Orbital mechanics
  - Micro-gravity
  - Orbital inclination
  - Day/night cycles
- Thermal conditions
- Radiation
- Micrometeoroids
- Atomic oxygen

5c. Spacesuit Equipment

This subsection focuses on the knowledge necessary to safely operate a spacesuit. The items below represent the types of equipment that would likely be found on a flight-class spacesuit, but due to innovations that will no doubt come from an expanding market, it is not inclusive. If a spacesuit utilizes a unique system, there is an expectation that the training program for that spacesuit would address the unique hardware. A training program should address nomenclature, operations and any on-orbit required maintenance.

- Primary breathing-gas system
- Secondary breathing-gas system
- Spacesuit internal environment
  - Example: pure oxygen vs. air
- Primary carbon dioxide removal system
- Primary cooling system
- Secondary cooling/carbon dioxide removal system
- Communications system
- Caution and warning system (to address spacesuit malfunctions and emergencies)
- Servicing umbilical system
- Pressure regulation system
- Electrical system
- Video system
  - Example: helmet camera
- Thermal control system
  - Example: glove heaters
- Humidity control system
- Biomedical monitoring system
- Lighting system
  - Example: helmet lights
- Hydration system
- Human waste collection system
  - Example: maximum absorbency garment
- Mechanical systems
  - Hard and soft structures
    - Examples: thermal micrometeoroid garment (outer layer), pressure bladder
  - Axial restraints
  - Circumferential restraints
  - Bearings and seals
  - Fans
  - Latches
- Visor and sunshades
- Sizing and ergonomics
- Range of motion
- Comfort items
  - Example: shoulder padding
- Reusable vs. expendable items
  - Example: maximum absorbency garment – expendable
- Restrictions:
  - Example: oil-based products are not to be used in a pure oxygen environment
- Operational risks
  - Example: an electrical system short in a pure oxygen environment
- Unique hardware
  - Example: electronic heads-up display providing Earth-overlay maps and spacesuit data

5d. Spacesuit Emergencies

This subsection addresses spacesuit failures that would require the spacewalker to immediately abort the EVA and ingress the spacecraft or risk the loss of life. A training program should address the failure, indications of the failure, and the appropriate response procedure.

- Loss of suit pressure
- Loss of suit integrity
- Electrical system short

5e. Spacesuit Malfunctions

This subsection addresses spacesuit malfunctions that may or may not require the spacewalker to take immediate action, but does not require the spacewalker to immediately abort the EVA and ingress the spacecraft. A training program should address the malfunction, indications of the malfunction, and the appropriate response procedure.

- Loss of:
    - Cooling system / subsystem
    - Communications system / subsystem
    - Carbon dioxide removal system / subsystem
    - Electrical system / subsystem
    - Caution and warning system / subsystem

5f. Medical Problems Associated with Spacewalking

This subsection addresses the medical problems associated not just with spaceflight, but with EVA. A training program should address the causes, symptoms, prevention and treatment of any common medical problem associated with EVA. NOTE: This list would necessarily require the review and approval of medical professionals experienced in the field of EVA.

- Spacesuit depressurization
    - Gas expansion (ears, sinuses, lungs, stomach, intestines, and teeth)
    - Lung overpressurization / overexpansion
- Spacesuit repressurization (squeezes/barotraumas)
    - Ear
    - Sinuses
    - Lungs
    - Teeth
- Other hazards
    - Decompression sickness (this topic should include an explanation regarding the need for the denitrogenation protocol used during EVA preparation)
    - Nitrogen narcosis
    - Excessive carbon dioxide / overexertion
    - Hyperventilation
    - Air poisoning / air contamination
    - Space adaptation sickness
    - Nausea
    - Spacesuit fit injuries
    - Claustrophobia
    - Fatigue and exhaustion
    - Stress and panic
    - Hypothermia
    - Overheating
    - Disorientation / vertigo

5g. EVA Preparation

This subsection addresses the various activities that must be performed prior to the start of an EVA. There will be considerable variation in the durations of these tasks, as many of them depend significantly upon the spacesuit design (including the designed operating pressure, and the overall complexity), the spacecraft design (including the nominal atmospheric pressure), and the interfaces between the spacecraft and the spacesuit. A training program should address the proper procedures to accomplish each step in the process of EVA preparation.

- Spacesuit servicing
- Spacesuit pre-EVA configuration
- Spacecraft / airlock pre-EVA configuration
- Tool configuration
    - Examples: digital still cameras, tethers
- Undergarment donning / doffing
- Spacesuit donning / doffing
- Denitrogenation protocol
- Carbon dioxide system conditioning
- Spacesuit depressurization / repressurization
- Post-EVA cleanup and reconfiguration

5h. EVA Operations

This subsection addresses the various activities performed and hardware utilized during an EVA. A training program should address the proper procedures for the operation of all hardware, and the operational constraints associated with each spacewalking task.

- Spacecraft / airlock nominal depressurization and repressurization
- Spacecraft / airlock hatch operations
- Servicing umbilical mate / demate
- Spacecraft / airlock egress and ingress
- Translation protocol, including:
  - Spacecraft translation paths
  - Spacecraft keep-out zones
  - Micrometeoroid strikes (creating sharp edges along translation paths)
- Communication protocol
- Tether management
- Tool operations
  - Example: digital still camera
- Photography techniques
- Body restraint at view-points

5i. EVA Emergencies

This subsection addresses emergencies that could occur during a spacewalk that would require a Spacewalker, 2nd Class to take immediate action, or risk injury or loss of life.

- Spacesuit emergency of any kind
- "Man overboard" rescue techniques
  - Self
  - EVA partner
- EVA partner loss of consciousness
- Spacecraft / airlock emergency repressurization protocol

5j. Neutral-Buoyancy Training

This subsection addresses the training objectives during neutral-buoyancy training in a water tank facility used to simulate low-Earth orbit. A training program should address the proper procedures and techniques required to operate safely and successfully in the vacuum of low-Earth orbit.

- Training session pre-brief
- Nominal operations
  - Spacecraft / airlock hatch operations
  - Spacecraft / airlock egress and ingress
  - Translation
  - Tether management
  - Body restraint
  - Tool operations
  - Communication
  - Spatial awareness
  - Situational awareness
- Emergency operations
  - "Man overboard" rescue techniques
    - Self
    - EVA partner
  - Incapacitated EVA partner rescue
  - Spacecraft / airlock emergency ingress and repressurization
- Training session debrief

5k. Vacuum Chamber Training

This subsection addresses the training objectives associated with spacesuit operations at vacuum. A flight-qualified spacesuit provides an individual the opportunity to experience spacewalking conditions as part of the pre-flight training program. A training program should address proper procedures and techniques to safely operate the spacesuit in a vacuum.

- Training session pre-brief
- Nominal operations
  - Reach assessment
  - Mobility assessment
  - Spacesuit fit assessment
  - Low-pressure effects
- Off-nominal operations
  - Malfunctions procedures
  - Simulated loss of cooling
  - Simulated loss of comm.
  - Simulated loss of suit integrity
- Training session debrief

6. Neutral-Buoyancy Training Parameters: Spacewalker, 2nd Class

Formal classes are essential to convey all the information needed to learn about spacewalking, but no lectures can substitute for the experience gained in training in a spacesuit in a neutrally-buoyant environment. The validation of neutral-buoyancy training came from Gene Cernan. After completing Gemini IX in 1966, in which he conducted just the second American EVA, Cernan repeated his tasks in NASA's Water Immersion Facility (WIF), and reported that his experience in the neutrally-buoyant environment of the WIF was nearly identical to his experience on orbit [15]. Since that time, NASA has utilized neutral-buoyancy facilities to train and prepare its EVA astronauts.

The following is a set of parameters that provide guidance in constructing a neutral-buoyancy training program. NASA has fine-tuned its EVA training program to optimize output in the EVA environment of space, without overwhelming students with superfluous information. The goal of NASA's EVA ASCAN (Astronaut Candidate) and Skills programs is to develop all the necessary attributes that lead to EVA success [8]. The lessons learned in the development of that program provide practical guidance for a commercial spacewalk training program.

- An individual should train in a neutrally-buoyant environment at a minimum training ratio of 5:1. If, for example, an individual was scheduled to perform one (1) four-hour EVA in low-Earth orbit, said individual should undergo a minimum of 20 hours of training in a neutral-buoyancy facility. This ensures adequate time to develop the skills in translation, tether management, tool operations, egress and ingress, and body restraint, necessary for a safe and successful low-Earth orbit spacewalk.

- A training program should provide clear, concise objectives for each neutral-buoyancy training event. The training team should engage in a pre-brief prior to each training event to clearly state the desired training objectives. At the completion of each training event, the training team should conduct a debrief to provide constructive, critical feedback for all skill-areas that require improvement.

- A training program must provide sufficient recovery time between neutral-buoyancy training events. The risk of physical injury, due to 1) the specific spacesuit design, 2) repetitive motion within the spacesuit and 3) individual spacesuit fit, will dictate the amount of mandatory time between training events. For example, excessive moisture on the hands, combined with physical friction within the spacesuit glove, can lead to fingernail delamination. Without adequate recovery time, such problems can be compounded, and can eventually lead to permanent injury.

- The duration of *at least* two neutral-buoyancy training events must exceed the scheduled low-Earth orbit EVA time. This ensures an individual has had adequate experience operating in the spacesuit for the designated length of time. Fatigue, especially hand fatigue, becomes a significant contributor to increased risk with increased EVA duration. It is advisable that a training program utilize a progressive approach, gradually lengthening the amount of time an individual spends in a spacesuit, in the neutrally-buoyant environment. By this, an individual can build endurance as the training program progresses, not unlike a marathon runner methodically adding distance over time to a training program.

- It is advisable that a neutral-buoyancy training program focus on technique and problem solving. A neutrally-buoyant environment cannot precisely mimic the challenges of low-Earth orbit. For example, it is difficult to start one's motion, and easy to stop one's motion in the neutrally-buoyant environment of a water tank, due to hydrodynamic drag. In the micro-gravity environment of low-Earth orbit, however, it is easy to start motion and difficult to stop motion. Therefore, neutral-buoyancy training should focus on solving the problems that present themselves, be they flight-like or not. An individual's ability to resolve any issue in a neutrally-buoyant environment gives the tools needed to solve different, yet equally challenging issues in low-Earth orbit.

- It is advisable for an individual to spend as much time as possible in a neutrally-buoyant environment under the direct mentorship of a Master Spacewalker. By placing a Master Spacewalker in the water alongside a student, the Master Spacewalker can demonstrate proper techniques, procedures and protocols. NASA utilizes a combination of engineers, who are experts in EVA training, and veteran astronaut spacewalkers (termed Instructor Astronauts) to train rookie spacewalkers in the art and science of spacewalking [11].

- It is advisable that a training program possess the capability to use hi-fidelity training-class hardware of 1) the actual spacesuit in which an individual will perform an EVA in low-Earth orbit, and 2) the actual spacecraft upon which an individual will perform an EVA in low-

Earth orbit. Experience has shown that there is no substitute for training with hardware built as close to flight-like specifications as possible [8].

7. Conclusion

Commercial spaceflight is on the horizon, and there will soon be more private astronauts than government astronauts. The private exploration of space will start in low-Earth orbit, but someday expand beyond, to destinations like near-Earth objects, whose natural resource value may fuel the emergence of a space mining industry. The ability to procure resources from such distant destinations will take skills not yet attainable to the general public.

The construction of the International Space Station is a testament to the power that can be harnessed through spacewalking. A world-class laboratory orbits the Earth some 200 miles above, providing a platform for experimentation that yields significant results, making the world a better place to live. The world of commercial spacewalking will provide a framework that will redirect the course of humanity.

It is not yet even in its infancy, but it is not difficult to imagine the possibilities that will become reality someday soon, not unlike the revolution that came with the advent of SCUBA diving. Although the sea has played a significant role in society for millennia, it was not until 1942 that Emile Gagnan, Jacque Cousteau's colleague, redesigned an on-demand pressure valve and "modern free-diving was born. At last there was a self-contained underwater apparatus (SCUBA) with which anyone could explore the underwater world [13]."

As with SCUBA diving, the accessibility will increase, as stories told by those first commercial spacewalkers ignite desire and passion within a daring but growing sect of society. Spacewalking will progress from a sightseeing adventure, to become a skill in high demand, whether that skill be used to construct an orbiting hotel, repair a damaged satellite, or drill for valuable resources on distant asteroids. And yet, it will be that most human of desires – to connect personally with one's environment, and in this case, to personally connect with the universe itself – that will drive those who seek to make spacewalking not just an experience, or a career, but a way of life. None of that, however, will be possible without programs that teach the art of spacewalking. It is the hope of this paper that it can act as a "first draft" of the standards that may one day lead to such a way of life.

To paraphrase Jacque Cousteau, *space, once it casts its spell, holds one in its net of wonder forever.*

Acknowledgements

The author would like to thank United Space Alliance for its sponsorship to the 2010 International Astronautical Congress. The author would also like to thank Mr. Grant Slusser, for guidance in assembling what the author hopes is a comprehensive list of standards for commercial spacewalking, and Dr. Sandra Moore for providing a concise editorial review. Any oversight or error in course content is the author's alone.

References

[1] American Academy of Underwater Sciences, Standards for Scientific Diving, AAUS (http://www.aaus.org), Nahant, MA, 11/2006, pp. 65-71.

[2] Association of Diving Contractors International, Consensus Standards for Commercial Diving and Underwater Operations, 5th Edition, ADCI (http://www.adc-int.org), Best Publishing Company, Flagstaff, AZ, 2004.

[3] American National Standards Institute, Standard Z86.3-1989 For Underwater Safety – Entry-Level Scuba Certification-Minimum Course Content, ANSI (http://www.ansi.org), New York, NY, 1989.

[4] American National Standards Institute, ANSI/ADCE-01-2009 For Divers – Commercial Diver Training – Minimum Standard, ANSI (http://www.ansi.org), New York, NY, 2009.

[5] Bove, A., Davis, J., Diving Medicine, 3rd Edition, W.B. Saunders Company, Philadelphia, PA, 1997.

[6] Bove, A., Medical Examination of Sport Scuba Divers, Medical Seminars, Inc. San Antonio, TX, 1998

[7] Federation Aeronautique Internationale, FAI Sporting Code, Section 8 – Astronautics, FAI Astronautics Commission (http://www.fai.org), Lausanne, Switzerland, 2008, pp. 4.

[8] Moore, S.K., Gast, M.A., 21st Century Extravehicular Activities: Synergizing Past and Present Training Methods for Future Spacewalking Success, Acta Astronautica, Volume 67, Issues 7-8, October-November 2010, pp. 739-752

[9] National Aeronautics and Space Administration, Composite Air-to-ground and Onboard Voice Tape Transcription of the GT-4 Mission (U), NASA, Washington, D.C., August 31, 1965, pp. 54. (http://www.jsc.nasa.gov/history/mission_trans/GT04_TEC.PDF)

[10] National Aeronautics and Space Administration, Crew Training Catalog, Multilateral Advanced/Increment-specific Training Plan (MA/ITP), SSP-50170, 2010.

[11] National Aeronautics and Space Administration, Extravehicular Activity Standard Operating Procedures (SOP), Revision B. NASA-JSC: MOD CB-QMS-004 Revision B, June 2009.

[12] National Association of Underwater Instructors, Technical Courses, NAUI (http://www.naui.org), website retrieved 07, 2010.

[13] Norton, T., Stars Beneath the Sea: The Pioneers of Diving, 1st Edition, Carroll and Graf, Publishers, Inc, New York, NY, 2000, pp. 5.

[14] Occupational Safety and Health Administration, 29 CFR Part 1910, Subpart T - Commercial Diving Operations, Directive Number: CPL 02-00-143,OSHA (http://www.osha.gov), Washington, D.C., August 11, 2006.

[15] Portree, D.S.F., Trevion, R., Walking to Olympus: An EVA Chronology, Monographs in Aerospace History Series #7, NASA, History Office, Office of Policy and Plans, Washington, D.C., 1997.

[16] Russell, F., The Pilgrims and the Rock, American Heritage, Volume 13, Issue 6, October 1962, pp. 48-55.

[17] Supervisor of Diving, Naval Sea Systems Command, US Navy Diving Manual, 5th Revision, AquaPress Publishing, Essex, United Kingdom, 2007

Commercial Spacewalking: Designing an EVA Qualification Program for Space Tourism

Matthew Gast
United Space Alliance, LLC
Houston, TX

Introduction

"This is the Saddest moment of my life…"

- Edward White,
at the end of the
first U.S. spacewalk

Gemini 4 – June 3, 1965

Introduction

- Scope
- Spacewalk Categorization
  - Spacewalker, 2nd Class
  - Spacewalker, 1st Class
  - Master Spacewalker
- Eligibility
- Minimum Course Content
- Neutral-Buoyancy Training Parameters, Spacewalker, 2nd Class
- Conclusion (The future of spacewalking)

Scope

- Spacewalk – Extravehicular Activity (EVA)
- Spacewalking vs. Scuba Diving
  - Diving Industry
    - Recreational, Technical and Scientific Diving
      - Self-Regulation
    - Commercial Diving
      - Government Regulation (OSHA, USCG)
  - Spacewalking
    - What is the appropriate level of regulation?
    - What are the appropriate certification standards?

Spacewalking Categorization

- Categorization:
  - To differentiate the roles, responsibilities and thus the certification requirements
  - This delineation creates three separate categories:
    - Spacewalker, 2^{nd} Class
      - Basic certification
      - The standards set forth in this paper will focus on this certification level
    - Spacewalker, 1^{st} Class
      - Advanced certification
    - Master Spacewalker
      - Highest certification

Spacewalking Categorization

- Spacewalker, 2nd Class
  - Meets the minimum qualifications to perform a *non-complex* EVA in low-Earth orbit under direct supervision
  - Certification Level Rationale
  - Analogous to recreational scuba diver
    - Self-regulation, due to operational limits set by the certification standards
    - Standards set by ANSI Z86.3-1989
    - Spacewalker, 2nd Class standard will follow similar format

Spacewalking Categorization

- Spacewalker, 1st Class
  - Meets the minimum qualifications to perform a *non-complex* EVA in low-Earth orbit without direct supervision
  - Certification Level Rationale
  - Analogous to technical/scientific scuba diver
    - Self-regulation; made exempt from government regulation in 1982, due to operational limits set by the certification standards
    - OSHA recognizes the American Academy of Underwater Scientists (AAUS) as the standard-setting organization
    - Spacewalker, 2nd Class standard will follow similar format

Spacewalking Categorization

- Master Spacewalker
  - Meets the minimum qualifications to perform *complex* EVAs in low-Earth orbit
  - Certification Level Rationale
  - Analogous to commercial diver
    - Government regulation; rules set by such government agencies as OSHA and the USCG
    - Standard set by ANSI
    - Spacewalker, 2nd Class standard will follow similar format

Eligibility

- Due to the risks, an individual should meet a set of prerequisites:
  - *Age* – at least 18 years of age; no upper limit
  - *Scuba Certification* – possess a scuba certification card prior to the beginning of training, due to
    - The use of a neutrally-buoyant training facility requires scuba certification
  - *Medical Certification* – obtain medical clearance to engage in the rigors of EVA training
    - Until a spacewalking-specific medical exam is developed, the "Diving Medical Exam" from the AAUS may represent an initial supplementary standard
  - *Knowledge* – pass a written exam that tests entry-level knowledge of all appropriate training categories
    - *Examples: Spacesuit equipment, medical problems, EVA operations*
  - *EVA Skills* – demonstrate to a Spacewalking Instructor entry-level capability at all skills needed to safely conduct an EVA in low-Earth orbit
    - This evaluation should utilize both a neutral-buoyancy training facility, and a human-rated vacuum chamber

Minimum Course Content – Spacewalker, 2nd Class

- General Guidelines
  - Addresses guidelines that equate to EVA best-practices, helping limit the associated risk
    - EVA planning
      - Overview of training and flight, rules and regulation, spaceflight provider-specific information
    - Minimum/maximum crew complement
      - The number of Spacewalkers, 2nd Class for each Master Spacewalker
    - Roles and Responsibilities
      - Spacewalker, 2nd Class
      - Master Spacewalker

Minimum Course Content – Spacewalker, 2nd Class

- Space Environment
  - Addresses the physical conditions an individual experiences during an EVA in low-Earth orbit
    - Orbital mechanics
      - Microgravity
      - Day/night cycles
      - Orbital inclination (and expected ground tracks for Earth observation)
    - Thermal conditions
    - Radiation
    - Micrometeoroids

Minimum Course Content – Spacewalker, 2nd Class

- Spacesuit Equipment
  - Addresses the knowledge needed to safely operate a spacesuit, including:
    - Primary breathing-gas system
    - Thermal control system
      - Example: glove heaters
    - Caution and warning system
      - To address spacesuit emergencies and malfunctions
    - Sizing and ergonomics
    - Operational risks
      - An electrical system short in a pure oxygen environment

Minimum Course Content – Spacewalker, 2nd Class

- Spacesuit Emergencies
  - Addresses spacesuit failures that require an immediate EVA abort, or risk loss of life
    - Electrical system short
    - Loss of spacesuit pressure
      - Example: micrometeoroid strike
    - Loss of spacesuit integrity
      - Example: glove cut on a sharp edge

Minimum Course Content – Spacewalker, 2nd Class

- Spacesuit Malfunctions
  - Addresses spacesuit malfunctions that do not require an immediate EVA abort
    - Loss of:
      - Cooling system/subsystem
      - Communications system/subsystem
      - Carbon dioxide system/subsystem
      - Electrical system/subsystem
      - Caution and warning system/subsystem

Minimum Course Content – Spacewalker, 2nd Class

- Medical Problems Associated w/ Spacewalking
  - Addresses the medical problems associated with spacewalking
    - Spacesuit depressurization
      - Gas expansion (lungs, ears, sinuses, teeth, stomach)
    - Spacesuit repressurization (squeezes/barotraumas)
      - Squeezes/barotraumas (ears, sinuses, lungs, teeth)
    - Other hazards
      - Decompression sickness
      - Hyperventilation
      - Spacesuit fit injuries
      - Disorientation/vertigo

Minimum Course Content – Spacewalker, 2nd Class

- EVA Preparations
  - Addresses the various activities that must occur prior to the start of an EVA
    - These will vary significantly, based on the spacecraft design, spacesuit design, and spacesuit/spacecraft interfaces
    - Spacesuit servicing
    - Tool configuration
      - Example: digital still camera
    - Spacesuit donning/doffing
    - Denitrogenation protocol

Minimum Course Content – Spacewalker, 2nd Class

- EVA Operations
  - Addresses the various activities performed and hardware utilized during an EVA
    - Spacecraft/airlock nominal depress/repress
    - Spacecraft/airlock hatch operations
    - Spacecraft/airlock egress and ingress
    - Translation protocol
      - Spacecraft translation path and keep-out zones
    - Communication protocol
    - Tether management
    - Photography techniques

Minimum Course Content – Spacewalker, 2nd Class

- EVA Emergencies
  - Addresses emergencies that could occur during an EVA that would require a Spacewalker, 2nd Class to take immediate action or risk loss of life
    - Spacesuit emergency of any kind
    - “Man overboard” rescue techniques
      - Self and EVA partner
    - EVA partner loss of consciousness
    - Spacecraft/airlock emergency repress protocol
      - Not an emergency in and of itself, but defines the actions necessary to perform expedited spacecraft ingress

Minimum Course Content – Spacewalker, 2^{nd} Class

- Neutral-Buoyancy Training
  - Addresses the training objectives to develop the skills necessary to safely perform an EVA in low-Earth orbit
    - Training session briefings
    - Nominal operations
      - Egress and ingress, tether management, tool operations, body restraint, situational awareness, spatial awareness
    - Emergency operations
      - “Man overboard” rescue techniques, incapacitated EVA partner rescue, emergency ingress and repress

Minimum Course Content – Spacewalker, 2nd Class

- Human Vacuum Chamber Training
  - Addresses the training objectives to develop the skills necessary to safely operate the spacesuit in vacuum
    - Training session briefings
    - Nominal operations
      - Reach and mobility assessments, spacesuit fit assessment, low-pressure effects
    - Off-nominal operations
      - Malfunction procedures, simulated loss of cooling, simulated loss of comm., simulated loss of suit integrity

Neutral-Buoyancy Training Parameters – Spacewalker, 2nd Class

- Training Parameters
  - Provide guidance in constructing a neutral-buoyancy training program
    - Training ratio – 5:1 (5 hours of neutral-buoyancy training for every hour of expected EVA time)
    - Training interval – sufficient to limit spacesuit-induced injuries
    - Training event duration – at least two training events should exceed the expected EVA time
    - Focus – the training program should focus on technique and problem solving, since a neutrally-buoyant facility cannot precisely mimic the microgravity of low-Earth orbit
    - Mentorship – a program founded on constant mentorship produces the most effective, efficient results
    - Fidelity – training should be conducted on hi-fidelity spacecraft and spacesuit training hardware

Conclusion

- The Future of Spacewalking
  - Commercial spacewalking will begin as an observational endeavor, much like scuba diving recreationally upon a barrier reef
  - It will transform into a commercial endeavor, with Master Spacewalkers constructing, for example, orbital hotels, and performing satellite repair
  - The natural resources of near-Earth objects will extend commercial spacewalking beyond low-Earth orbit
  - It all begins, however, with training programs that teach the art of spacewalking to anyone with the desire to make that personal connection with the world beyond our own

Conclusion

- To paraphrase Jacque Cousteau:

“Space, once it casts its spell,

holds one in its net of wonder forever…”