SAFETY OF SPACEFLIGHT PARTICIPANTS ABOARD SUBORBITAL REUSABLE LAUNCH VEHICLES – BACKGROUND RESEARCH

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ABSTRACT

The anticipated advent of the U.S. Government sponsoring human-tended research on commercial suborbital flights necessitates the establishment of safety review procedures for federal agencies to allow government-sponsored spaceflight participants (SFPs) aboard these vehicles. Safety practices for National Aeronautics & Space Administration (NASA) personnel aboard aircraft, orbital rockets and platforms, and a non-NASA vehicle, the *Soyuz*, are summarized. The valuable "Recommended Practices for Human Space Flight Occupant Safety," published by the FAA Office of Commercial Space Transportation (FAA-AST) in 2014, are summarized. Medical recommendations for operationally critical flight crewmembers, published by the Aerospace Medical Association Commercial Spaceflight Working Group, are reviewed. FAA-AST-approved SFP training available at three U.S. commercial companies is summarized. Activities of ASTM International Committee F47 on Commercial Spaceflight, formed in 2016, are reviewed. Finally, safety comparisons are made with another challenging environment, deep sea submersibles.

1. INTRODUCTION

At the urging of industry advocates, the U.S. Congress is encouraging the emergence of commercial space capabilities by limiting government regulatory requirements for developers/providers [Commercial Space Launch Act (1984), extended by Commercial Space Launch Amendments Act (Public Law 108–492, Dec. 23, 2004)]. Like other commercial spaceflight providers, commercial suborbital Reusable Launch Vehicle (sRLV) providers are licensed under FAA-AST regulations to provide safety to the uninvolved public under a designated "learning period." In essence, commercial space providers are operating in a safety pre-certification era. As a commercial licensed activity, a sRLV provider can sell flights to the public for participation at their own risk. Identified as spaceflight participants (SFPs), they are informed that the vehicle has not been independently certified as safe by the FAA. They are informed of specific risks to potential personal harm and/or loss of life and must sign a waiver of liability based on informed consent. It is worth noting that FAA-AST has developed and published recommended practices for human spaceflight occupant safety and training, discussed later, to serve as guidelines for developers during this learning period. These recommended practices are intended to be translated into a regulatory safety certification regime after the learning period expires.

2. FAA AND NASA FLIGHT PARTICIPANT SAFETY PRACTICES

For commercial and private aviation, the FAA has established and modified rules over decades to ensure passenger safety. These rules incorporate proven maintenance standards and practices based on practical experiences and rigorous aircrew training standards and requirements. In contrast, NASA's aviation safety authority self-regulates NASA-sponsored personnel aboard public-use and non-NASA-controlled aircraft. The cognizant NASA Center Technical Authority oversees an independent safety review of the proposed aviation flight activity. Approval for a given flight or series of flights is granted after a comprehensive program review to determine if mission and safety risks have been identified and mitigated to acceptable levels. The scope of the review is based on the complexity and criticality of the aviation flight activity.

For U.S. astronauts, a NASA Procedural Requirements Document (NPR) establishes procedural and technical requirements for human-rating certification. Exceptions are the International Space Station (ISS) and *Soyuz* (and in an earlier revision, the Space Shuttle), which are not required to obtain a human-rating certification. Those latter programs "utilize existing policies, procedures, and requirements to certify their systems for NASA missions" [1].

The U.S. Commercial Space Launch Competitiveness Act of 2015 (H.R. 2262) created new category of NASA people flying on commercial rockets, viz., "Government Astronauts." This legislation allows highly trained astronauts to perform operations not allowed for SFPs.

The NASA Administrator identifies which flight occupants are so designated [2].

Soyuz is a series of spacecraft designed for the Soviet space program by the Korolev Design Bureau in the 1960s that remains in service today. NASA performed a study on safety of flight participants aboard the current version of the *Soyuz* and concluded that multiple solutions along an "arc of acceptability" (Fig. 1) have proven successful [3].

3. PARAMETRICALLY PROJECTED SAFETY OF SUBORBITAL RLVs

In 2013, the NASA Flight Opportunities Program sponsored research at The Aerospace Corporation to develop a model for predicting safety of new rocket-powered sRLVs. The approach was to evaluate effects of vehicle catastrophic failure on the vehicle provider's business case, focusing on demand vs. supply. This market focus emphasized "probability of failure" as opposed to the more conventional reliability modeling approach, based on "probability of success." The primary challenge was the need to bridge performance data and cultural differences across several distinct areas with scant data:

- Subsonic, supersonic, and orbital flight
- Expendable and reusable vehicles, human-rated and non-human-rated
- Old and new technologies
- Past vs. present concepts of safety (user and government culture)
- Vehicle end use (commercial, recreational, government, military)
- Differences in vehicle test programs (minimal versus extensive)

A parametric approach was employed to make predictions of sRLV safety using parametrics. The result was a safety comparison of a specific sRLV against other flight vehicle categories and activities. The predictions were based upon 2015 flight technology, Mach 3.5 maximum speed, professionally piloted human-rated systems, FAA controlled airspace/flight rules, FAA safety regulations, and flight profile and other variables, all programmed into the model. Safety of the examined sRLV was found to range across columns C and D in Tab. 1 [4,5]. The developed model can be a useful tool for comparing candidates to historical systems and constructing a business case analysis for newly developed flight vehicles [4]. The model responds to changes in parameters deemed important to flight safety and is calibrated to relevant history.

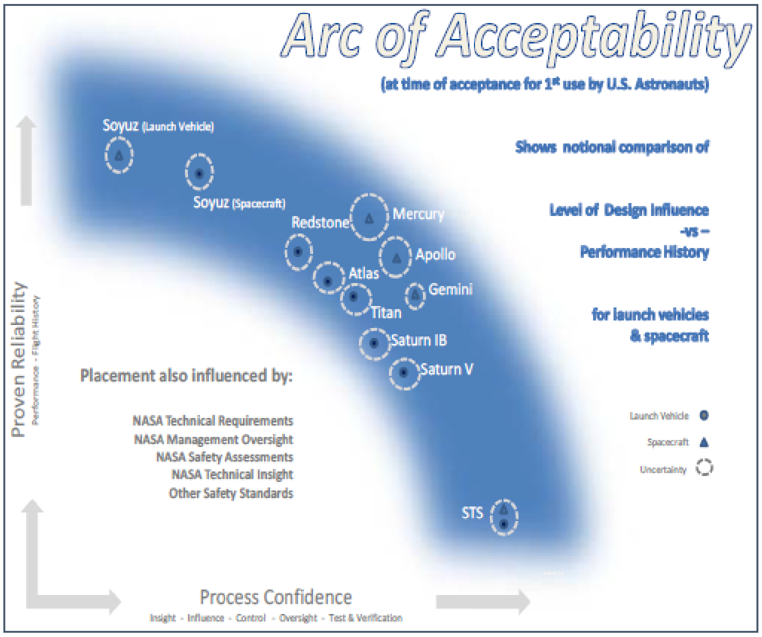

Figure 1. Arc of Acceptability [3]

4. VEHICLE GUIDELINES FOR SAFETY-CRITICAL AREAS OF sRLVs

Aerospace was tasked by FAA-AST in 2002-2003 to develop minimum vehicle guidelines for safety-critical areas of commercial RLVs, necessary to ensure the safety of flight crew and passengers. These guidelines were developed by reviewing and analyzing specifications, requirements, and lessons-learned for safety of commercial, military, and experimental aircraft, military space systems, and past and present human-carrying space systems, followed by interpolation and projection of these requirements for crew and passengers aboard both suborbital and orbital categories of future commercial RLVs. A bottoms-up approach was used to evaluate the following subsystems: environmental control and life support system; main propulsion system; guidance, navigation, and control system; avionics and software; main structural system; thermal protection system; thermal control system; health monitoring system; electrical power system; mechanical systems; flight safety system; and crew system [6].

5. SPACE WEATHER BIOLOGICAL AND SYSTEM EFFECTS FOR SUBORBITAL FLIGHTS

Aerospace and the ANSER Corporation were tasked by FAA-AST in 2008 to evaluate effects of space weather, including solar particle events (SPEs), on human biology and electrical systems in RLVs operating at suborbital altitudes from launch sites located in low (equatorial regions), middle, and high latitudes. The objectives were to (1) identify and describe typical dose rates and expected radiation hazards to crew and electronics on suborbital flights, including effects of solar cycle and extreme solar and geomagnetic events, and (2) based on the hazards identified, determine mitigation measures and safe phenomena threshold levels and then determine recommended flight rules to minimize space weather hazards based on results of the mitigation methods. There were two principal conclusions. First, owing to the short duration of flights (~30 min. or less) and the even shorter exposure at altitudes where atmospheric shielding is significantly reduced (~5 min.), the exposure of crew and passengers is minimal, except under circumstances where SPEs occur, which is less than about 5% of the time. Under typical conditions, the radiation exposure to crew and passengers on a suborbital flight is less than that for a long duration airline flight. Secondly, avoiding exposure to potentially harmful radiation associated with solar or geophysical disturbances can be achieved by locating launch sites at middle latitudes, or lower, or by delaying flights when there are indications that an SPE is in progress or imminent. For a high-latitude site, a possible launch commit criterion could be based on event probability distributions [7]

6. CONGRESSIONALLY MANDATED SFP INFORMED CONSENT

U.S. Legislation (Commercial Space Launch Amendments Act, 2004, and U.S. Commercial Space Launch Competitiveness Act, 2015) gives FAA-AST authority to regulate commercial spaceflight but does not allow the FAA to regulate the safety of people aboard space vehicles. Instead, the law requires informed consent of onboard crew and passengers. The occupants must state in writing that they (1) understand that the U.S. Government has not certified the space launch or reentry vehicle as safe and (2) have been informed of the risks of the vehicle they are boarding and others like it [8]. Note that waiver of liability and informed consent are two different things. For example, NASA does not allow their civil servants to grant liability waivers on commercial sRLVs in the performance of their official duties.

Table 1. Probability of Catastrophic Failure or Fatalities for Flight Vehicles and from Other Activities [4,5]

A: Expected ($Pr > 10^{-1}$)	B: Probable ($10^{-1} \geq Pr > 10^{-2}$)	C: Likely ($10^{-2} \geq Pr > 10^{-3}$)	D: Unlikely ($10^{-3} \geq Pr > 10^{-6}$)	E: Improbable ($Pr \geq 10^{-6}$)
• **New ELVs** (first 10 launches) • U.S. Civil War (Union) • WWII U-Boat • High-Altitude Mountaineering	• **Orbital Launch** (All vehicles) • **STS** • **XB-70** • Normandy (D-Day) • Grand Prix Racing • Base Jumping	• **X-15** • Hang Gliding • Motorbike Racing	• **Concorde** • Automobiles • Skydiving • Bungee Jumping • Swimming • Fire	• **General Aviation** • Skiing • Lightning Strike

7. U.S. HUMAN SPACEFLIGHT SAFETY RECORD

The FAA Office of Commercial Space Transportation has compiled a comprehensive summary of the U.S. human spaceflight safety record and posted it on their website [9]. The purpose is to provide data to facilitate the ability of SFPs to make informed consent decisions. This safety record is shown in Tab. 2 and 3.

8. RECOMMENDED PRACTICES FOR HUMAN SPACE FLIGHT OCCUPANT SAFETY

FAA-AST has developed and published recommended practices for human spaceflight occupant safety and training, to serve as guidelines for developers during the statutory-mandated learning period. This document, "Recommended Practices for Human Space Flight Occupant Safety" [10], is intended to be translated into a regulatory safety certification regime after the learning period expires. To develop this document, FAA-AST worked closely with NASA, industry, and other key stakeholders. The document was the culmination of a 3-year effort, which involved researching existing human spaceflight standards, conducting a series of public teleconferences to gather recommendations, and soliciting feedback from the Commercial Space Transportation Advisory Committee (COMSTAC). FAA chose to primarily use NASA's requirements and guidance for the Commercial Crew Program (1100 Series) as a guide. The purpose was not to copy NASA's requirements, but to use them to capture relevant safety concepts.

The FAA document addresses occupant safety only. Public safety and mission assurance are not directly addressed. Both orbital and suborbital flights are covered. Orbital vehicles are defined as those that stay on orbit for 2 weeks maximum and can return to earth in under 24 hours if necessary. Orbital rendezvous and docking, long duration flights, extravehicular activity, and flights beyond earth orbit are not explicitly covered. The period of coverage is from when occupants are first exposed to vehicle hazards prior to flight through when they are no longer exposed to vehicle hazards after landing.

The document covers recommended practices in three categories, (1) Design (human needs and accommodations, human protection, flightworthiness, human/vehicle integration, system safety, and design documentation), (2) Manufacturing, and (3) Operations (management, system safety, planning, procedures & rules, medical considerations, and training). No specific level of safety (risk) is defined due to the expected wide variety of systems and flight profiles. Two levels of care are articulated: (1) occupants should not experience an environment during flight that would cause death or severe injury (a low bar), and (2) the level of care for the flight crew when performing safety critical operations is increased to a level necessary to perform those operations. In an emergency the same level of care is not expected to be maintained – only a reasonable chance of survival is mandated. Key assumptions were: (1) Each flight crew member is safety-critical, (2) SFPs may be called upon to perform limited safety-critical tasks, and (3) Clean sheet philosophy – no other regulations act to protect occupants from harm. There are several notable omissions: First, although medical consultation is recommended, SFPs are free to assess their individual risk. Secondly, long-term health issues from ionizing radiation are not addressed. Third, integration of occupant and public safety is an area for future FAA-AST work.

9. INTERNATIONAL ASSOCIATION FOR THE ADVANCEMENT OF SPACE SAFETY (IAASS) GUIDELINES

The IAASS is establishing a commercial Space Safety Institute to offer safety certification services on a commercial basis. Guidelines are being developed by IAASS using the experience accumulated in more than 60 years of government space programs. These requirements are intended to protect the flight personnel (i.e., crew and SFPs), the vehicle and relevant launcher or carrier, and any other interfacing system from spaceflight hazards.

Table 2. U.S. Human Spaceflight Safety Record [9]

Launch Type	Total # of People on Space Flight	Total # People Died or Seriously Injured[3]	Total # of Human Space Flights	Total # of Catastrophic Failures[6]
Orbital (Total)	921[1]	17	164[4]	3
Suborbital (Total)	208[2]	3	204[5]	2
Total	1129	20	368	5

- **§ 460.45(c).** An operator must inform each space flight participant of the safety record of all launch or reentry vehicles that have carried one or more persons on board, including both U.S. government and private sector vehicles. This information must include—
  (1) The total number of people who have been on a suborbital or orbital space flight and the total number of people who have died or been seriously injured on these flights; and
  (2) The total number of launches and reentries conducted with people on board and the number of catastrophic failures of those launches and reentries.

Table 3. Footnotes from Table 2 [9]

1. People on orbital space flights include Mercury (Atlas) (4), Gemini (20), Apollo (36), Skylab (9) and Space Shuttle (852)
   a) Occupants are counted even if they flew on only the launch or reentry portion. The Space Shuttle launched 817 humans and picked up 35 humans from MIR and the International Space Station
2. People on suborbital space flights include include X-15 (169), M2 (24), Mercury (Redstone) (2), SpaceShipOne (5) and SpaceShipTwo (8)
   a. Only occupants on the rocket-powered space bound vehicles are counted per safety record criterion #11
3. Deaths and serious injuries include X-15 (1), Apollo-Soyuz Test Project (3), Challenger (7), Columbia (7) and SpaceShipTwo (2)
   a) Deaths or serious injuries that occurred when there was no intent to launch (e.g. Apollo 1 fire), are not counted per safety record criterion #9
   b) Alan Bean during splashdown on Apollo 12 suffered a concussion. The FAA uses the NTSB's definition of serious injury (criterion #13), but the NTSB does not consider a concussion itself a serious injury. The FAA will remain consistent with the NTSB and not count this incident as a serious injury
4. Orbital flights include Mercury (Atlas) (4), Gemini (10), Apollo (12), Skylab (3) and Space Shuttle (135)
5. Suborbital flights include X-15 (169), M2 (24), Mercury (Redstone) (2), SpaceShipOne (5) and SpaceShipTwo (4)
   a) Glide flights are not counted per safety record criterion #2
   b) Flights that fail to meet the definition of suborbital rocket in 14 CFR § 401.5 are not counted (thrust must be greater than lift) e.g. some X-15 and M2 flights
6. X-15 Flight 191, Challenger STS-51-L, Columbia STS-107, SpaceShipTwo VSS Enterprise, Apollo-Soyuz Test Project

10. MEDICAL ASSESSMENT OF HUMANS FOR FLIGHT

For NASA operations, medical assessment of aviation pilots and space astronauts is performed to ensure they are medically qualified for flight duties [11]. The medical examiner acts on behalf of the regulatory agency to help ensure safety of flight. The examination is performed to meet specific requirements and or concerns that must be satisfactorily addressed before a safe flight can be implemented. The 1% rule denies issuing a medical certificate to an airline pilot if their risk of a medical incapacitation (e.g., heart attack, convulsion, stroke, fainting, etc.) is determined to be greater than 1% per annum. Also, medical surveillance is maintained.

A report by the FAA Civil Aerospace Medical Institute (CAMI) provides general guidance for operators of manned commercial aerospace flights (suborbital and orbital) in the medical assessment of prospective passengers [12]. Two categories of passengers are discussed, (1) passengers participating in suborbital aerospace flights (or exposed to G-load of up to +3Gz during any phase of the flight), and (2) passengers participating in orbital aerospace flights (or exposed to G-load exceeding +3Gz during any phase of the flight). The report discusses acceleration risks associated with the neurological, cardiovascular, and musculoskeletal systems as well as medical conditions that may contra-indicate passenger participation in suborbital or orbital flights and disposition of prospective passengers with these conditions. The report's medical considerations were considered in FAA-AST's "Recommended Practices for Human Space Flight Occupant Safety," discussed above.

The Commercial Spaceflight Working Group of the Aerospace Medical Association has proposed recommendations for operationally critical flight crewmembers participating in suborbital spaceflight [13]. The recommendations are:

- An FAA first-class medical certificate using same age-based schedule as for Airline Transport Pilot (ATP) pilots
- Pre-flight medical evaluation
- Post-flight medical debrief with data collection
- An independent data repository of medical findings
- Periodic reevaluation of the current medical standards during the early stages of developmental flights
- Passive ionizing radiation dosimeters worn by each flight crewmember
- Auditory protection in the helmet or headset for all crewmembers
- Emergency egress training for all crewmembers
- Physiologic training (altitude chamber) to ensure flight crew recognition of signs and symptoms associated with decompression, including hypoxic changes
- Recent centrifuge or other G training
- Anti-G suit use on flights until more experience has been obtained
- Parabolic flight training
- Pressure suit use for commercial spaceflight operators
- Further investigation on effects on pilot performance from rapid changes in the acceleration/microgravity/entry deceleration flight profile

11. SPACEFLIGHT PARTICIPANT TRAINING

Three SFP training centers have been approved by FAA-AST:

- National AeroSpace Training and Research (NASTAR) Center, Southampton, PA
    - http://www.nastarcenter.com/aerospace-training/space/passengers
    - FAA Safety Approval No's. SA 10-001, SA 12-004
- Black Sky Training, Colorado City, TX
    - https://www.blacksky.aero/index.shtml?trainingsf
    - FAA Safety Approval No's. SA 13-005A, SA 14-006
- Waypoint 2 Space, Houston, TX
    - https://www.waypoint2space.com/
    - FAA Safety Approval No. SA 14-007

NASTAR offers Basic Suborbital Space Training, a 2-day program designed to provide future space travelers with the core knowledge and skills to become a safe, confident, and capable suborbital SFP. The program addresses:

- Aerospace Environment
- Space Vehicles & Flight
- Motion Environment & Orientation
- Acceleration Forces
- Life Support Systems and Suits
- Space Experience
- Physiological and Psychological Effects
- G Protection, Countermeasures & Skills
- Space Safety and Emergency Procedures
- Maximizing Spaceflight Experience
- Keeping and Preserving Space Memories
- G-Tolerance Flights and Simulated Space Flights

NASTAR also offers Advanced Space Training, a 2-day program designed to provide enhanced knowledge and in-depth training including emergency preparedness that goes above and beyond the basic space training course. The program addresses:

- Altitude Physiology
- Spatial Disorientation
- Situational Awareness
- Emergency/Rapid Decompression
- Emergency Procedures & Operations
- Personal Safety & Health
- Aerospace Medicine
- Loss of Control In-flight (LOC-I) Preparation & Flights
- Situational Awareness and Spatial Disorientation Preparation & Flights
- Altitude Chamber Preparation & Flight

Finally, NASTAR offers Space Payload Specialist training and Space Suits and Systems Training. Their equipment includes a Phoenix centrifuge (3 fully controllable axes with continuous 360° pitch and roll, and real-world displays and controls), an altitude chamber that provides a safe, controlled and medically monitored setting to conduct high altitude research or training, and a Gyrolab GL-2000 that provides uniquely controlled, sustained G-force with its planetary axis, and 360° rotation in 3 axes. [http://www.nastarcenter.com/aerospace-training/space/passengers]

For Black Sky Training, the FAA-AST website lists two active safety approvals: (1) Crew & Spaceflight Participant Training, and (2) Scenario Based Physiology Training. [https://www.blacksky.aero/index.shtml?trainingsf]

Waypoint 2 Space offers three levels of spaceflight training. *Level 1* is a one-week, fully immersive training program designed for anyone interested in spaceflight to experience training. The program includes launch and reentry g-forces, microgravity, mission control operations, crew resource management, astronaut suit fit and pressurization checks, exploration of foreign surfaces, extravehicular activity (EVA) training using gravity offset equipment and a neutral buoyancy environment, normobaric chamber, orbital mechanics and flight dynamics, spacecraft docking maneuvers, Lunar/Mars terrain negotiation using rover exploration vehicles, and virtual reality space simulations.

Waypoint 2 Space's *Level 2* training participants spend three days in rigorous suborbital space environment training designed for a specific flight profile and vehicle. Each participant learns and experiences how limited exposure to weightlessness and G-forces associated with rocket powered flight affect the body. The training prepares the participant to take full advantage of 5 to 7 minutes of weightlessness during their flight. Participants learn normal and safety procedures in preparing for emergency situations in dynamic spacecraft simulations including hypoxia recovery, smoke and fumes emergency procedures, and work as a crew through situational awareness training.

Waypoint 2 Space's *Level 3* Orbital Training Program is scheduled to begin in 2020 and is intended to consist of eight weeks of rigorous training for the orbital space environment. The program expands to twelve weeks with EVA training. Participants will experience a multitude of test scenarios that include aspects such as spatial disorientation, emergency depressurization procedures, vehicle malfunctions, and contingency operations. Trainees will experience relevant human factors, psychological and physical, that must be mastered before prolonged spaceflight. The program is designed to increase situational awareness preparing participants to live and operate in space. [https://www.waypoint2space.com/]

12. ASTM-INTERNATIONAL COMMITTEE F47 ON COMMERCIAL SPACEFLIGHT

In 2016 ASTM International (formerly American Society for Testing and Materials) formed Committee F47 on Commercial Spaceflight to address privatization and commercialization of spaceflight [https://www.astm.org/COMMITTEE/F47.htm]. Industry is utilizing ASTM's neutral forum to develop safety and quality standards and recommended practices to facilitate positioning for future regulatory requirements as well as innovation in this progressing area. The Committee meets three times annually, with about 30 members attending 1 to 2 days of technical meetings, in conjunction with industry conferences.

The F47 committee has 9 technical subcommittees that develop and maintain these voluntary consensus standards. Two of the subcommittees are addressing human spaceflight safety: (1) Subcommittee F47.01, Occupant Safety of Suborbital Vehicles, and (2) Subcommittee F47.02, Occupant Safety of Orbital Vehicles. Subcommittee F47.01 is developing a new guide, "Fault Tolerance for Occupant Safety of Suborbital Vehicles."

13. COMPARISONS WITH ANOTHER CHALLENGING ENVIRONMENT: DEEP SEA SUBMERSIBLES

Deep sea submersibles must survive another challenging environment for human safety. Representative active submersibles, each owned by a national government, include:

- U.S.: *DSV-2 Alvin*, to 4,500 m., owned by the U.S. Office of Naval Research (ONR), operated by Woods Hole Oceanographic Institution (WHOI)
- Australia: *Deepsea Challenger* (DCV 1), carried Titanic director, James Cameron, to ocean's deepest point, Challenger Deep, >10,900 m.
- France: *Nautile*, to 6,000 m.
- Japan: *Shinkai*, to 6,500 m.
- China: *Jiaolong*, to 7,500 m.

Cyclops 2, in development by a U.S. commercial company, OceanGate, Inc., is a 5-person submersible designed for descent to 5,000 m. [http://www.oceangate.com/pdf/oceangate-cyclops-2.pdf].

Human safety in government submersibles is assured via a detailed systems certification approach. For example, safety of *Alvin* is controlled by a 350-page

NAVSEA manual specifying detailed certification procedures for materials and components, design factors, testing parameters, life support systems, airborne contaminants, and much more [14]. As discussed earlier, the U.S. government does not yet require that type of certification for sRLVs. FAA-AST’s role regarding sRLV safety is limited to licensing and regulating until a later date when the industry is mature.

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