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Review of the *FAA Recommended Practices for Commercial Spaceflight Occupant Safety*

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Abstract

In 2014, the FAA published its first set of Recommended Practices for commercial crew spaceflight safety. These guidelines purvey several fundamental, systemic errors. The five major findings that expose these flaws include:

- Failure to address whether "one size fits all" for the diverse proposed commercial crew spacecraft,
- Avoidance of existing human spaceflight design and operating standards,
- Profound problems with the clarity of the language, particularly the subjunctive tense in which all the recommendations are written,
- Conflating the requirements for the flight crew and the passengers, and
- The omission of risk management and reliability strategies.

The central cause of these pervasive flaws would appear to derive from the FAA's ambivalence toward regulating commercial spaceflight as opposed to promoting it. The FAA wants to frame the regulatory regime with good intentions without dictating to the commercial companies how to conduct their business of flying people in space for profit. This approach creates situations in which the recommended practice is not appropriate for the problem it seeks to solve. This review covers the major findings that came out of the section-by-section gap analysis.

1. Introduction

This investigation began when the author received a subcontract from the Florida Institute of Technology (FIT) in 2018 to review the Federal Aviation Administration's (FAA) Recommended Practices for Human Spaceflight Occupant Safety 1.0 (2014, Aug 27). The FAA evidently required—and FIT requested—that reviewers evaluate each numbered section or subsection in the Recommended Practices by filling out a *gap-analysis* matrix in spreadsheet form. The underlying assumption was that the existing text was still valid and applied to current and future concepts for commercial crew spaceflight. However, the motivating concern was that there may be some areas or topics arising in the fast-developing commercial spaceflight industry that the Recommended Practices do not yet cover. It was not stated explicitly that the FAA was seeking corrections to possible errors, leaving it possible to assume that it was seeking only new material to cover omissions or "gaps."

In beginning to review these Recommended Practices, the expectation was to just fill out the gap-analysis spreadsheet to provide incremental mark-ups with citations, and references. The matrix provided for recommendations concerning existing language, but did not afford cells or rows to make assertions or recommendations about new or additional areas of concern.

Instead of complacently filling out all the cells provided in the matrix, the review process discovered a pattern of ***fundamental, systemic errors in the Human System Integration and Safety methodology.*** This paper responds to these discoveries by characterizing the overarching concerns that frame the systemic errors and omissions. The simple point is that although none of these issues appear as a cell or "gap" in the analytical matrix; all existed before publication of the Recommended Practices. These concerns continue to exist and often may achieve greater clarity with the continuing progress and maturation of commercial crew spacecraft.

In purveying these five fundamental, systemic errors in the Recommended Practices, the FAA reveals a deep ambivalence regarding the FAA's prospective role as a regulator of commercial spaceflight and specifier of requirements for it. They also reveal an aversion to the existing design standards and operational practices of that rival agency, NASA. It is not meaningful to discuss the gap analysis of the text on a section-by-section basis without first addressing these overarching defects. The major findings that expose these flaws include:

- Does One Size Fit All? The new commercial crew spacecraft involve multiple diverse modes of launch, spaceflight, and landing. Historically, NASA has written vehicle-specific standards for each type of spacecraft (e.g., Apollo Command Module, Space Shuttle Orbiter, International Space Station). The Recommended Practices make no assertion that it is possible to write one set of guidelines that apply to all commercial spacecraft.

- The Recommended Practices omit any mention of existing human spaceflight design, integration, and operations standards. NASA and its major aerospace contractors (e.g. Boeing, Lockheed, Northrop Grumman) systematically write standards documents for each of their projects and missions (e.g. the historic NASA Standard 3000, the Man-System Integration Standard). The Recommended Practices do not betray any awareness of these standards that dominate government- and corporate-funded crew spacecraft.

- The Recommended Practices display profound problems with the clarity of the language, particularly the subjunctive tense in which the authors wrote all their good intentions. Instead of the standard *shall* or *will* that appear in normal standards documents, the FAA weasel-words its statements with the moral exhortation *should.* The problem with using the subjunctive in this way is that it is never clear

- The title of the Recommended Practices refers to *occupants.* The use of this term evades the distinctions between crew and their responsibilities and the passengers who fly with far fewer responsibilities. This conflation of crew and passengers leads to avoidance of any question of occupational exposure for the crew which will be much more frequent and extensive than for passengers. (e.g. artificial atmosphere, microgravity, radiation, vibration).

- The presentation of risk management and reliability strategies in the Recommended Practices fails to achieve a rudimentary level of maturity or understanding. No doubt the FAA prefers to relegate all risk to the companies flying commercial spacecraft, but that is hardly an excuse to fall below the professional standard of care.

The central cause of these pervasive flaws appears to derive from the FAA's dual roles in promoting commercial spaceflight while presumably anticipating its incipient role in regulating it. These two roles create potential contradictions in the lines of authority and ambiguity in the FAA's role in possibly enforcing these *Recommended Practices* as requirements. The FAA appears to want to frame the regulatory regime with good intentions without dictating to the commercial companies how to conduct their business of flying people in space for fun and profit. This ambiguity—either unintended or intended—could lead to confusion, misapprehension, miscommunication, human error, and perhaps tragedy.

2. The Gap Analysis

The design of this review involves completing a gap analysis on a spreadsheet. Prof. Ondrej Doule at the Florida Institute of Technology composed the spreadsheet for reviewers to fill out the following columns for each paragraph, section, and sub-section. Normally, this approach to conducting a gap analysis should suffice, and it did for most of the operative statements in the paragraphs.

- Paragraph: The numerical designation of the paragraph that contains a recommended practice.
- Gap: Identify the Gap in the sense that the Recommended Practices fail to cover or cover incompletely a technical or operational topic.
- Recommendation: Design, Manufacture (Development, Production).
- Recommendation: Operations (End-User)
- Reference/Explanation

This analytical matrix sufficed to evaluate the Recommended Practices on their own terms. The paragraph constituted the text of each numbered section of the Recommended Practices. Thus, all commentary and gap analysis went precisely to the existing text. However, the problem that this reviewer encountered concerned to topics that did not appear in the original text.

The major omissions identified arose when the necessary paragraph on a key topic was missing. For example, the only reference to ionizing radiation asserted that the FAA was not interested in risks with long-term effects, so there was no paragraph or section on ionizing radiation and protecting the crew and passengers from it. This strategy reflected the attitude that the FAA was not interested in longer-term occupational exposures that might affect the crew. Another type of omission arose where the "paragraph" listed the topics but did not make any recommendation about them. Instead the "rationale" paragraph that followed gave a detailed explanation but refrained from making or asking for a recommendation.

3. Caveat about Baseline Research

Before going into the Major Findings, it is only fair to recognize the disadvantage under which the FAA labored in creating the Recommended Practices. Not only were they not empowered to regulate the commercial crew spaceflight industry, but they apparently did not have the resources — financial, personnel, supporting consultants — to do the baseline study necessary to establish a solid foundation in crew spaceflight safety practices and policies within private industry. As a counter-example before NASA began promulgating safety requirements and standards for the International Space Station (ISS), it commissioned the five-volume Station Crew Safety Alternatives Study from Rockwell Crew Safety that was involved in overseeing Space Shuttle operations (Peercy et al, Vol. 1; Raasch et al, Vol. II; Rockoff et al, Vol. III; Peercy et al, Vol. IV; Mead et al, Vol. V; 1985).[1]

Sgobbo and Kezirian (2016, pp. 6-7) do an excellent job of describing the US legislative and regulatory history and regime for commercial crew spaceflight. One of their two key points are that for the FAA to develop a well-researched and valid system of safety regulation it may benefit from NASA's experience:

> In the initial phase of the Crew Commercial Program NASA made an inventory of existing technical standards and recommended them either as reference baseline (meet or exceed) or as good practices, stating that *"In the course of over forty years of human space flight, NASA has developed a working knowledge and body of standards that seek to guide both the design and the evaluation of safe designs for space systems"*. [sic] (p. 7, original emphasis).

Sgobbo and Kezirian (p. 9) elucidate this point by drawing a comparison between NASA's institutional infrastructure and that of the FAA. NASA does not play a regulatory role in Commercial Crew Spaceflight, but rather suggests standards and recommends improvements:

> The competence of NASA's multi-disciplinary safety review panels, and of the specialist teams and labs that support them is well known, but this is a rather unique circumstance, that has no match in traditional regulatory organizations. This means that an obvious substitute for NASA's technical skills does not currently exists for non-NASA commercial human spaceflight orbital and sub-orbital projects, although badly needed. If tomorrow FAA would be allowed to regulate crew and flight participant safety of commercial spaceflight, the problem would become apparent. Industry, collectively, has the means to solve it.

Sgobbo and Kezirian's second key point is that the policies and practices of all the commercial crew spaceflight companies need to be made available for review (p. 10):

> It is in the best interest of industry, and of all stakeholders, to publish the safety policies and technical best-practices they apply during design, manufacturing and operations of commercial space vehicles.

To sum up, FAA needs to do the detailed gruntwork of studying the internal design, manufacturing, and operational policies and practices of the existing commercial crew spaceflight companies. Only in this way can the FAA learn enough to craft effective, knowledgeable and reasonable regulations.

4. Major Findings of Systemic Errors and Omissions

As overviewed in the Introduction, this review found five instances of systemic omissions and errors. These topics consist of:

- Does one size fit all?
- Avoidance of existing standards,
- Lack of clear language,
- Conflating the flight crew with the passengers, and
- Omission of risk and reliability strategies.

4.1 FIRST SYSTEMIC FINDING: Does One Size Fit All?

This first systemic finding derived from the lack of awareness or mention of any specific commercial crew spacecraft taxonomy or typology. The prospective diversity of the commercial human spacecraft industry suggests that such a taxonomy is currently developing. The candidate commercial human spacecraft at present include:

1. Scaled Composites/Virgin Galactic SpaceShipTwo
2. SpaceX Crew Dragon
3. Blue Origin New Shepard
4. Sierra Nevada Dream Chaser
5. Boeing ST-100 Starliner
6. SpaceX Starship
7. Copenhagen Suborbitals

This systemic finding presents a brief illustrative description of each candidate spacecraft to portray the variety not just in crew cabin but in launch, trajectory, flight operations including docking, re-entry, and landing. TABLE 1 presents a *précis* of the significant differences plus some commonalities among the several

[1] Full Disclosure: The author was involved in oversight and review of all five volumes, and served as contract monitor for Volume III, Safety Impact of Human Factors.

commercial crew spacecraft now under development. It lays a conceptual framework for future safety regulations.

4.1.1 Scaled Composites/Virgin Galactic SpaceShipTwo

Scaled Composites was the first private company to begin developing its own commercial crew spacecraft without any government funding. The performance envelope is a suborbital trajectory. The intended market is space tourists who will experience microgravity for up to about 15 minutes before beginning descent, re-entry, and landing. Scaled Composites developed also the White Knight 2 as the first custom-designed carrier aircraft to convey the SpaceShipTwo to an altitude of about 15,250 m (50,000 ft.). At that altitude White Knight 2 releases the SpaceShipTwo, which drops away from its carrier then fires its engine to kick up to the suborbital target altitude. The rule of thumb for achieving suborbital flight is to cross the Karmen line at the nominal top of the Earth's atmosphere of 100 km (62 mi., or 327,000 ft.). To commence re-entry, the pilot "feathers" the wings to create atmospheric drag and slow the spacecraft. SpaceShipTwo descends and lands on a runway much like a piloted aircraft. Virgin Galactic has landing rights at the SpacePort America facility in Truth or Consequences, New Mexico, which it envisions as its operational hub. One unique feature of the SpacesShip2 is that it is the only one of the commercial crew vehicles that limits its flight envelope to suborbital trajectories. By definition, these flight durations are 15 minutes or less. However, it is conceivable that SpaceShipTwo could evolve to an intercontinental passenger-carrying travel system. Views of SpaceShipTwo and White Knight 2 appear in FIGURES 1 to 4.

FIGURE 1. SpaceShipTwo carried aloft (in the center) under White Knight 2. Note the similarity of the cockpit and forward fuselage design. Courtesy of Scaled Composites/Virgin Galactic.

FIGURE 2a. SpaceShipTwo in its first test flight with wings positioned close to the fuselage.

FIGURE 2b. SpaceShipTwo firing engine in ascent to suborbital trajectory. Courtesy of Scaled Composites/Virgin Galactic.

FIGURE 3. SpaceShipTwo with its wings in "feathered" position to commence its descent and re-entry. Courtesy of Scaled Composites/Virgin Galactic.

FIGURE 4a. SpaceShipTwo mockup interior view. Courtesy of Virgin Galactic.

FIGURE 4b. SpaceShipTwo cockpit controls and displays and the forward windows. Courtesy of Virgin Galactic.

FIGURE 4c. Beth Moses, Virgin Galactic astronaut seated in the SpaceShipTwo cockpit. Courtesy of Purdue University.

4.1.2 SpaceX Crew Dragon

The SpaceX Dragon unscrewed spacecraft was the first commercial cargo vehicle to deliver supplies and equipment to the ISS. The Dragon is the only commercial spacecraft with a demonstrated capacity for cargo in advance of its first crew launch. With its quasi-hemispherical shell (trailing end during re-entry), the form-factor of the Crew Dragon's ire-entry capsule bears more similarity to the Soyuz capsule than to the Apollo frustoconical model. The Crew Dragon's design is intended to carry up to seven crewmembers to low Earth orbit (LEO). The Crew Dragon can re-enter the atmosphere and return to Earth with comparable "payload" of crew, passengers, and cargo. With its array of windows all around the fuselage, the design of Crew Dragon shows its purpose to serve as a space tourism vehicle. Because it is an orbital spacecraft, it is possible for Crew Dragon to convey space tourists for a week or more after launch. Crew Dragon launches atop a SpaceX Falcon 9. It makes a parachute water landing. FIGURES 5 to 8 show views of the Crew Dragon.

FIGURE 5. SpaceX unscrewed Crew Dragon launches atop a Falcon 9 rocket. Courtesy of SpaceX.

FIGURE 6. Artist's CAD rendering of a Crew Dragon approaching the docking port on the ISS. Courtesy of SpaceX.

FIGURE 7a. Astronaut Sunita Williams working in the Crew Dragon simulator, April 2018. Courtesy of SpaceX.

FIGURE 7b. SpaceX Crew Dragon V2 spacecraft interior view, showing seating for seven crew. Courtesy of SpaceX

FIGURE 8. Space X Crew Dragon splashdown after flight test. Photo courtesy of NASA.

4.1.3 Blue Origin New Shepard

Blue Origin may be unique insofar as it aims its New Shepard capsule for both the suborbital tourist market and for orbital service in LEO. The New Shepard clearly is designed with sightseeing passengers in mind with its large windows—the largest in any crew spacecraft. The New Shepard headed to orbit will launch atop Blue Origin's New Glenn rocket and will be capable of reaching the ISS in LEO. Besides carrying crew and passengers, the cargo-carrying capacity of New Shepard is not yet clearly established. The landing mode for return from orbit is presumably a parachute water landing. The New Shepard offers the option of a suborbital trajectory. It is possible that Blue Origin plans to make the suborbital return to Earth end in a vertical, propulsive landing with an upper stage booster still attached. FIGURES 9 to 12 show views of New Shepard.

FIGURE 9. New Shepard launch, June 19, 2016 on a prototype single-stage suborbital rocket. This suborbital variant would perform a powered vertical landing. Courtesy of Blue Origin.

FIGURE 10. New Shepard capsule return parachute descent test. Courtesy of Blue Origin.

FIGURE 11. View of the New Shepard capsule interior. Courtesy of Blue Origin.

FIGURE 12. Picture from Blue Origin, portraying the anticipated delight of space tourists looking out the window while in micro–g. Courtesy of Blue Origin.

4.1.4 Sierra Nevada Dream Chaser

The Dream Chaser is a lifting body concept that follows more closely in the tradition of the Space Shuttle than any of the other commercial crew spacecraft. Although originally designed to launch vertically atop a rocket, Dream Chaser—or perhaps a scaled-down "3/4" size version—may be able to ascend on the Stratolaunch carrier aircraft or perhaps the White Knight 2. With these several launch options, Dream Chaser appears to present the most versatile combination in terms of ascending to orbit. Dream Chaser can carry crew and cargo to LEO and dock to the ISS.

Dream Chaser would presumably be capable of suborbital as well as orbital flight trajectories. The location of the docking port in the aft end is not unique; the French/ESA *Hermes* lifting body concept placed its docking port there in the 1980s. Dream Chaser returns from orbit in a mode very similar to the Space Shuttle, to land on a landing strip or dry lake bed. FIGURES 13 to 17 present views of Dream Chaser, with particular attention to its multiple potential launch configurations.

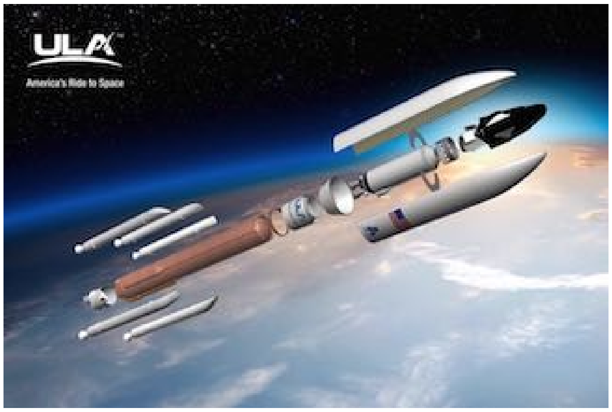

FIGURE 13. This ULA graphic shows an exploded view of a Dream Chaser configured inside a launch fairing to sit atop an Atlas rocket with side boosters plus a second stage booster. Courtesy of ULA.

FIGURE 14. This artist's rendering shows a Dream Chaser launching atop an Atlas rocket without the ULA fairing. Courtesy of Sierra Nevada Corp.

FIGURE 15a. Dream Chaser mounted on a "second stage" booster carried by the Stratolaunch aircraft. Courtesy of Sierra Nevada Corporation.

FIGURE 15b. This rendering by Maxwell shows a reduced-scale Dream Chaser being carried aloft by the White Knight 2 carrier aircraft. The absence of the "second stage" booster may imply that this configuration is for a sub-orbital flight. Courtesy of Sierra Nevada Corp.

FIGURE 16. This photo from Sierra Nevada Corp. shows the Dream Chaser making a landing on a runway in California. Courtesy of Sierra Nevada Corp.

FIGURE 17. Dream Chaser cockpit flight simulator. Courtesy of Sierra Nevada Corp.

FIGURE 18. This CAD rendering from Sierra Nevada Corporation shows the Dream Chaser docked "tail-first" to the nadir ("–Z-bar") docking port on the Unity Node on ISS. Note the Soyuz spacecraft to the left in similar nadir docking position on the Russian segment. Courtesy of Sierra Nevada Corp.

4.1.5 Boeing ST-100 Starliner

The Boeing Starliner follows most closely upon the Apollo Command and Service Module paradigm of any of the commercial crew spacecraft. It's more recent heritage derives from Boeings 2004-2005 NASA Crew Exploration Vehicle Phase I contract and 2006 Orion Multipurpose Crew Vehicle Phase II competition.[2] The Starliner presents outwardly a conservative design insofar as it replicates Apollo. However, this similarity is deceptive. Starliner incorporates significant new design ideas. The first among these innovations is the "clam shell" design in which the entire upper shell can be detached from the lower backshell to facilitate outfitting, maintenance, and repair. A further innovation is the installation of solar panels over the aft end of the service module, eliminating the need to deploy and then retract solar arrays as on the Lockheed Martin Orion spacecraft.

Due to its Apollo heritage blunt body form, the Starliner may be the only commercial crew vehicle capable of performing a lunar mission. The difference between re-entry from LEO and from lunar orbit is dictated by difference in re-entry velocities. Re-entry from LEO occurs at about 11 km/sec whereas re-entry from the Moon occurs at about 17 km/sec. The difference in the q (the heating) of the spacecraft is determined by the cube of the velocity. Thus, the ratio of heating of a lunar-return vehicle to a LEO-return vehicle comes to about 3.7. Not only the heat shield material but the blunt body shape plays a critical role in protecting against the aerothermal heating burning up the spacecraft and its occupants.

FIGURE 19. Starliner launching on a ULA launch Vehicle. Courtesy of ULA.

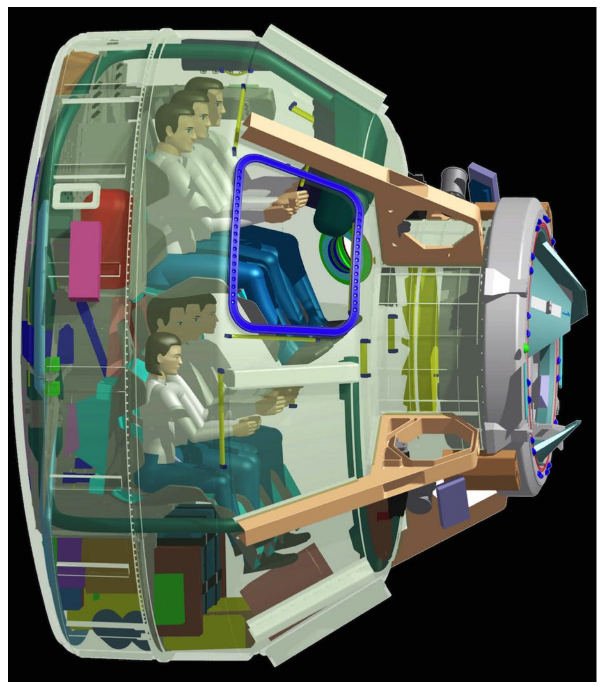

FIGURE 20. CAD view of the Starliner interior, showing the two tier seating, with three crew above in the piloting positions and two crew or passengers below.

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[2] Full disclosure: The author worked on the Northrop Grumman/Boeing team proposal for Orion Phase II, which produced the design upon which Starliner is largely based.

FIGURE 21. Boeing Starliner approaching the ISS to dock at the –V-Bar docking port on the Unity node. Note the extensible, impact absorbing docking collar. Courtesy of Boeing.

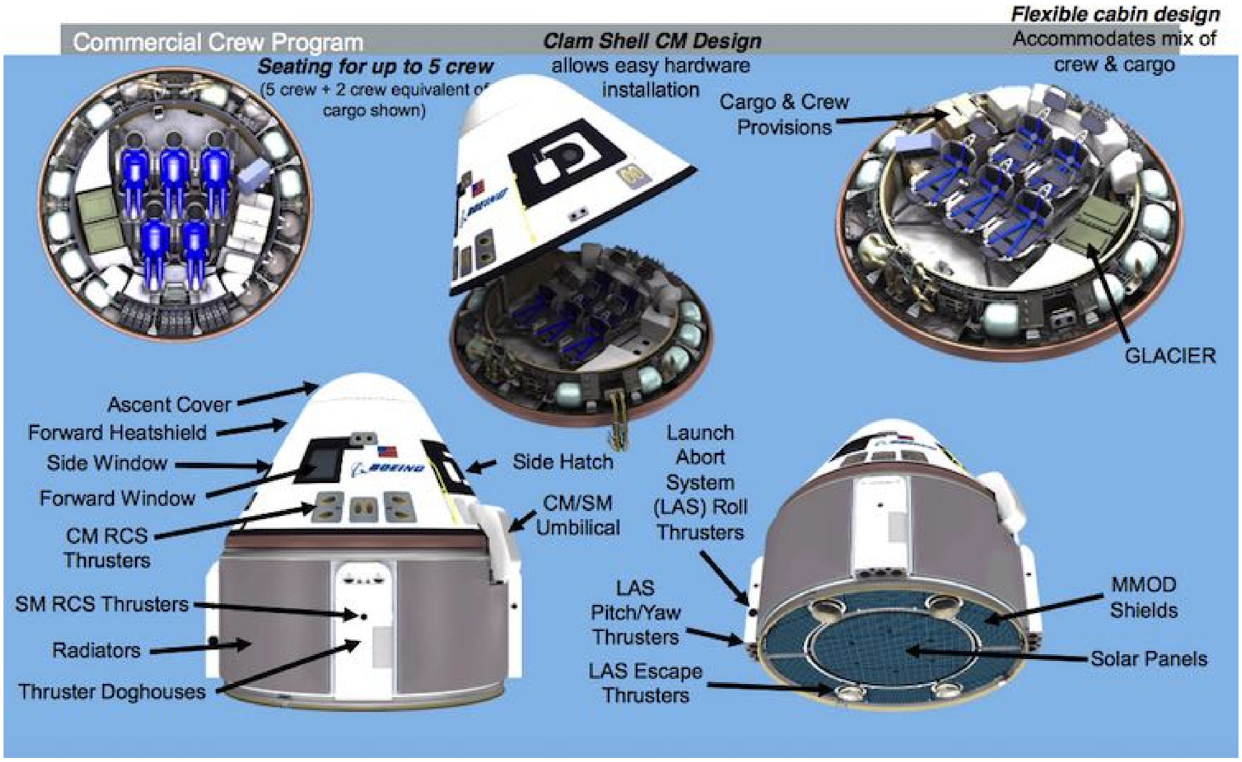

FIGURE 23. Assembly diagram for the CST-100 Starliner. Courtesy of Boeing. Top left shows a "plan view" of the array of five crew positions, three above and two below with their backs toward the backshell. Top center shows how the backshell detaches from the upper body to facilitate preparation for flight and refurbishment. Top right shows a perspective view of the backshell assembly. Bottom left shows an elevation of the assembled Orion stack with the Service Module, wrapped in radiators. Bottom right shows a perspective view of the Service Module, revealing the solar panels on its aft surface.

FIGURE 22. Astronaut working in the Starliner cockpit simulator.

4.1.6 SpaceX Starship

The SpaceX Starship is a newcomer to the commercial crew sweepstakes. The announced Starship missions are to carry humans to a colony on Mars, but long before that objective becomes realizable, it may well find other missions and operations closer to home. Given that SpaceX is a for-profit company, it is likely that these more near-term mission may have a commercial dimension. The Starship appears to incorporate its upper stage booster into the same airframe as the crew cabin. It will launch vertically atop an immense booster. As described by Elon Musk, it will land in vertical orientation on its upper stage booster. It is not yet clear how the crew exit and descend from the crew cabin in the absence of a launch gantry tower.

FIGURE 24 Space X Starship Assembly. Courtesy of SpaceX.

4.1.7 *Copenhagen Suborbitals' Beautiful Betty*

The one private crew spaceflight company outside the USA appears to be Copenhagen Suborbitals, a non-profit incorporated in Denmark. [3] Copenhagen Suborbitals is currently "crowdsourcing" funding and other resources for a suborbital crew flight over the Baltic Sea. Their spacecraft will carry one volunteer crewmember roughly in a manner and on a scale comparable to the Mercury Redstone configuration, that carried the first two NASA Astronauts, Alan Shepard and Gus Grissom. Copenhagen Suborbital's safety provisions are not in evidence at this writing. However, it is conceivable that they or a comparable start-up may someday seek to launch from within the territory of the United States, in which case they would fall under the purview of the FAA.

FIGURE 25. Copenhagen Suborbitals Launch Test concept. Courtesy of Copenhagen Suborbitals.

Because Copenhagen Suborbitals is neither commercial nor subject to the FAA's aegis, it falls outside the FAA's immediate purview. However, it is not much of a stretch to imagine Copenhagen Suborbitals or another "Do it yourself" club wanting to operate from US territory. In 10 to 20 years, it is conceivable that college clubs will be trying to launch their own crewed spacecraft just as today they launch their own cubesats. FIGURES 25 to 28 illustrate the Copenhagen Suborbitals' concept. FIGURE 26 shows Copenhagen Suborbitals original, naive single crew launch configuration. FIGURE 28 shows their most recent capsule configuration, the "Beautiful Betty."

FIGURE 26. Copenhagen Suborbitals early single crew capsule

[3] Full Disclosure: The author is a member of the AIAA Space Architecture Technical Committee, of which Kristian von Bengtson, President of Copenhagen Suborbitals was a member for a number of years at the same time.

FIGURE 27. Artist's rendering of Copenhagen Suborbitals launch above the Baltic Sea.

FIGURE 28. Advanced concept mock-up for the Copenhagen Suborbitals "Beautiful Betty" single person capsule, resembling a mini-Apollo capsule. Courtesy of Copenhagen Suborbitals.

4.1.8 Diverse Commercial Crew Spacecraft Launch, Flight, and Landing Modes

TABLE 1 presents the variety and complexity of the Commercial Crew Spaceflight industry's current development efforts to prepare and conduct flight operations. TABLE 1 illustrates the challenge to the FAA and to aviation regulatory agencies world-wide to understand all these highly individual systems with their strengths and weaknesses, advantages and disadvantages, reliabilities and vulnerabilities. It demonstrates Sgobbo's and Kezirian's point about doing a comprehensive study of each of these companies' practices and policies. Without such a detailed and thorough-going analysis ***to establish the regulatory framework***, it is difficult to conceive how the FAA can write one or more sets of regulations that will "add value" or safety to this nascent industry. TABLE 1 suggests the outlines of such a regulatory framework, covering the key operational phases of launch, suborbital trajectory or orbital injection, re-entry into the atmosphere, and landing.

TABLE 1 presents an inherent paradox insofar as some commercial crew spacecraft appear in many cells of the table whereas others appear in only two—one for launch and one for landing. It is probably too early even to speculate as to which paradigm will prove more advantageous in terms of market, operations, or profitability: multiple, "flexible" launch, orbit, and landing versus single mode of launch, orbit, and landing. This unpredictability illustrates just one aspect of this regulatory challenge. To wit: would the same regulations apply to a spacecraft on a suborbital flight as on an orbital flight to a private space hotel.

TABLE 1 principally compares the Orbital vehicles to the Suborbital vehicles. The first column indicates the vehicles with the capacity for Air Launch. The second column shows vehicles that can launch vertically from a launch pad. The third column indicates vehicles that make a piloted aerodynamic landing. The fourth column shows vehicles that make a parachute landing. The fifth column shows the vehicles that could make a powered, controlled landing. Finally, column six addresses the atmospheric entry/re-entry regime. Column six bears special importance because it illustrates the limitations on the various spacecraft to re-enter from orbit, or, what is more challenging, from a lunar return.

4.1.9 Aerothermal Re-entry

Aerothermal re-entry capability constitutes a new parameter that may be both enabling and limiting. A spacecraft's ability to make an atmospheric entry experiences an absolute constraint in terms of the amount of aerothermal heating it can handle and survive. This aerothermal heating, or Q varies as the cube of the velocity. TABLE 1 column 6 indicates both the entry velocity and the corresponding Q factor. At the top is the "special case" of lunar return of which only Boeing's Starliner is deemed capable at this time. Next comes the case for return from Low Earth Orbit (LEO), with velocity and Q. Finally, the suborbital cases with velocity and Q appear appear in the Suborbital row.

The break-through discovery at Ames Research Center that made possible and enabled much of the Space Age was H. Julian Allen's and Alfred J. Egger's revelation in 1951 that aerothermal heating varies inversely with aerodynamic drag. This insight led directly to the design of the blunt body entry vehicle, from which the Apollo Command Module derived its idealized shape. Among the present crop of spacecraft, only the Boeing Starliner reflects this blunt body geometry. However, SpaceX has applied the PICA ablative heat shield — which is capable of a ~12+ km/s entry — to the Dragon (Chambers, Rasky; 2011; p. 6), so it ****may**** be capable of lunar return re-entry.

TABLE 1. Commercial Crew Spaceflight Launch, Landing, and Flight Modes

Trajectory	Piloted Air Launch	Pad Vertical Launch	Piloted Aerodynamic Landing	Parachute Descent Landing	Powered Vertical Descent	Atmospheric Re-entry
Orbital Flight	Stratolaunch for Dream Chaser with Booster or "75% Dream Chaser?"	Dragon Starliner Dream Chaser New Shepard Starship	Dream Chaser & "75% Dream Chaser?"	Dragon Starliner New Shepard	Starship	**Lunar Return @ ~11 km/s *Q factor* = ~1331** Starliner Dragon? **LEO Return @ ~7.8 km/s *Q factor* = ~475** Dragon Starliner Dream Chaser New Shepard Starship
Suborbital Flight	SpaceShipTwo White Knight 2 for Dream Chaser?	New Shepard Beautiful Betty	SpaceShipTwo Dream Chaser	New Shepard Beautiful Betty	New Shepard	**Suborbital Return @~4.3 km/sec *Q factor* = ~80** SpaceShipTwo Dream Chaser New Shepard Beautiful Betty

4.2 SECOND SYSTEMIC FINDING: Avoidance of Existing Standards

Perhaps the most peculiar systemic error that emerged was the avoidance of all existing standards for human spaceflight design and operations. This paradox arises from the situation that it appears the authors adopted the format and style of the NASA Human Systems Integration Requirements (HSIR), which states each requirement (with the modal verb auxiliary *shall*) followed by a paragraph giving the rationale for that requirement. So, the authors were well aware of HSIR and probably other standards; the outline of section *1.4 Human/Vehicle Integration* reflects that awareness. While it might pose too much of a burden on the authors or the readers to insert a citation of every relevant standard, certainly the *Recommended Practices* would benefit from references to the key standards and requirements documents in the field of human spaceflight. The few mentions of standards occur at the introduction:

> The document can also be used to help identify subject areas that could benefit from industry consensus standards. There are a number of industry and government standards that address the subject areas covered in this document, but some subject areas may not have standards that are appropriate for the commercial human space flight industry. The development of industry consensus standards in these subject areas could have significant benefits for the safety of future commercial operations.
>
> Lastly, the document may serve as a starting point for a future rulemaking project, should there be a need for such an effort at some point in the future. However, ***this document is not a regulation, and it has no regulatory effect*** (Emphasis added. FAA, 2014, p. 1).

While this disclaimer makes the intent clear, the consequence of omitting such references to external reality and NASA experience in human spaceflight leaves the reader in a kind of Neverland where every one of the *Recommended Practices* conjures up its assertion by magic, untethered to any empirical evidence. The impression that none of the operative paragraphs appear to be anchored to any real world experience or engineering gives the FAA document a kind of fairy tale quality.

4.2.1 The Regulatory Void

However, there is much more at work here than what appears on the surface. According to George C. Nield, FAA Associate Administrator for Commercial Spaceflight:

> With the passage of the 2004 Commercial Space Launch Amendments Act (CSLAA) by the U.S. Congress, the U.S. Federal Aviation Administration's Office of Commercial Space Transportation (FAA/AST) was given clear authority to regulate commercial human space flight. However, in order for the new industry to grow and develop, Congress restricted the issuance of new regulations that were designed to protect the safety of the people onboard. . . .
>
> An eight-year period was established during which the FAA could not propose regulations for occupant (crew and space flight participant) safety (Nield, Sloan, Gerlach, 2014, pp. 1-2).

The timeline for the development of commercial human spaceflight played a role in the FAA's hands-off approach.

> By early 2012, with no commercial human flights since the Ansari X Prize was won in 2004, but with progress in suborbital development and a new NASA Commercial Crew Program underway, the Congress passed an extension of the "moratorium" on new regulations until October 2015. In addition, Congress instructed the FAA to enter into a dialog with industry to discuss potential human space flight regulations and practices. (Nield, Sloan, Gerlach, 2014, p. 2).

The work on the Recommended Practices began in about 2012, around the time that Congress extended the ban on regulation. The FAA published them in 2014, while still under the regulatory ban. Congress has since extended the ban again until 2023.

4.2.2 The Hands-off Approach and its Consequences

The consequence of this hands-off approach meant that the way the FAA authors wrote about many of the subject areas they covered was often not appropriate to those topics. This misfit occurred systemically in the operative language, which they wrote entirely in the subjunctive with the modal verb auxiliary "should." It also appears to have led to misunderstanding of risk management and reliability and the appropriate language to evaluate problems and implement solutions. What was most important, the author found in filling out the Gap Analysis was that due to a lack of technical and operational research, many provisions of the Recommended Practices were naïve at best, but often wee simply mistaken or incorrect. This shortcoming raises the imperative: How can the FAA require the sufficient and appropriate knowledge to actually regulate commercial crew spaceflight?

4.3 THIRD SYSTEMIC FINDING: Lack of Clear Language

Clarity of language is the first-order indicator of clarity of thought.

4.3.1 Bureaucratese Unleashed

The language of these Recommended Practices is highly problematic to the extent that it subverts the document's intent and message. As such the unclear and muddled use of prescriptive language throughout the document constitutes a fundamental and systemic error in the so-called recommended practices.

Ironically, it appears that the original manuscript was written in lucid, even elegant language with active verbs, logical flow, and expert knowledge of most of the technical topics. Then, someone—almost certainly from the government—went through it and added well over 100 awkward sentences in the subjunctive, using "should with" a clumsy passive verb structure. The word *should* appears 178 times, most often in the formulaic "The vehicle should be designed such that . . ." or, "The system should be designed such that . . ." This repetitive, awkward intrusion renders that part of the text into classic bureaucratese at the expense of clarity and of comprehending the important distinctions among the various threats to safety and the strategies to address them.

4.3.2 The Liabilities of the Subjunctive

What is missing from the all-subjunctive ***should*** consistency of the Recommended Practices, is the reality that the language used in actual requirements, specifications, or standards use ***shall*** *or* ***will*** as the modal verb auxiliary. *The vehicle shall provide* . . . coveys a third person imperative or obligatory statement. It refers to an unlimited future for the capability described in the predicate. Another puzzlement is that *should* is technically the past tense of shall. In common usage, it forms the subjunctive in English, but it does not express an unlimited future. Instead, it expresses a perfect action, as in the completion of a vehicle or the completion of the design of the vehicle. *Should* does not inherently imply the long-term performance capabilities of that vehicle.

4.3.3 The Costs of Ambiguity

This distinction cuts at least two ways. There is a huge difference in meaning between saying "the vehicle shall" and "the vehicle should" that is immediately obvious. One is subjunctive, a suggestion, and a moral argument. The other is an imperative, an obligation. However, there is an even larger and more important distinction between "the vehicle should" and "the vehicle should be designed such that . . ." The statement "The vehicle should provide" or even "The design of the vehicle should provide" is clear and direct in its simplicity and use of the active verb. The statement "The vehicle should be designed such that it provides . . ." is unclear, indirect, garbled, and ambiguous in using the passive verb. It does not say who designs the vehicle. In fact, the sentence lacks a subject, the party doing the designing.

4.3.4 Should in the Conditional Mood

Another peculiarity of the Recommended Practices is that it sometimes uses *should* in the conditional mood—instead of if-then, or if-would, it uses if-should. For example, in section 1.4.6 Occupant Communication, the Rationale states:

> *If an electronic communication device is not used, the habitable volume sound levels should be limited to allow for occupant communications.*

There is no reason to avoid or limit the use of the conditional mood, *per se,* but it injects the added burden that all the arguments of the conditional clause (the *if* /then clause) must be valid, even if the predicate appears ion the subjunctive *should*. In this example, the argument "an electronic communication device is not used" is **not valid** because there are many reasons why the crew or passengers in the spacecraft may not have the use of an available electronic communications system. To call it a device implies that it is something hand-held or integrated in a helmet or oxygen mask. However, the argument neglects many other possibilities: the Wi-Fi failed, the radio broke, the batteries died, and so on and on. Please remember this example when considering the section on Fail-Safe below.

4.3.4. The Price of Passive Verbs

One profound consequence of the use of passive verbs in nearly all the prescriptive statements is the near-universal absence of a subject in the sentence. In normal spoken or written language, the subject denotes who or what is acting through the verb. In nearly all of the prescriptive sentences lacking a subject, it is not possible to perceive who or what "should" do something or not do something. The Recommended Practices explain the role of the system and the vehicle, which in some cases the reader may infer at her own risk is the subject of the sentence. However, the Recommended Practices also occasionally introduce other subjects that it does not define. These subjects include "the operator," or "the manufacturer" or "the ground controller."

4.3.5 Defining Performance versus Process

Just because the Recommended Practices are a government publication does not require that the operative or prescriptive language be crafted so poorly that it misinforms or misdirects the intended audience. What this admonition means is that stating *how* to design the vehicle (*should be designed such that*) goes to process, it does not go to the product: the vehicle or the system. It does not address how the vehicle itself must perform in operation. Therefore, there is far greater value in prescribing how the product should perform than in prescribing how the process to accomplish that design or operational performance.

4.3.5 Recordkeeping and Documentation

Certainly, the requirement to "document what you do and do what you document" is a foundation stone of good system engineering, quality assurance, and system safety management—as well as ISO 9000 practices. However, establishing standards for record keeping, while a vital part of any safety strategy, does not equate to prescribing the design process. On the contrary, the record-keeping and documentation discipline should transcend the biases of performance, process, and production and stand on its own as a prerequisite to enabling effective and fair regulation.

4.4 FOURTH SYSTEMIC FINDING: Conflating the Crew with the Passengers

Perhaps the most puzzling failure is the inability or unwillingness of the authors to distinguish between the flight crew and their passengers. The Recommended Practices refer almost entirely to "occupants." However, there is an obvious and tremendously significant difference between them: the total amount of time they spend in the space environment. These distinctions apply to both brief sub-orbital flights and to longer-term flights up to the two weeks specified in the Recommended Practices. Those two weeks may represent a visit to the ISS or to a private space station *cum* space hotel.

4.4.1 Crew Occupational Exposures versus Passenger Exposures

The passengers on a suborbital flight may spend up to a half-hour in the space or near-space environment. They would not be subject to the long-term effects of weightlessness, but some may experience the most common short-term effect, "space sickness" consisting of nausea and vomiting. The Recommended Practices are silent on this problem except for cleaning up the vomitus. What is far more important is that the professional crews will be subjected to an additional range of repetitive occupational exposures in spaceflight, including but not limited to breathing an artificial atmosphere, high-g launch and landing, radiation, and vibration. Again, the Recommended Practices are silent.

4.4.2. Crew Flight Frequency

Compare the passengers' single flight to the crew on suborbital flights who—if one can believe the commercial spaceflight companies Concepts of Operation— may fly two to five times per week, and perhaps more often. That adds up to 300 hours per year or much more. That total time spent in space is probably not enough to trigger concern about prolonged exposure to weightless or radiation, especially on sub-orbital trajectories. However, what is more important for frequent sub-orbitals is the exposure to the high g-loads and the extreme vibrations of launch, re-entry, and landing. The commercial crews who go through this regime daily or more often will experience orders of magnitude more exposure to high-g, high-vibration levels than any previous space traveller, for whom spaceflights occurred often years apart. Surely, there must be some medical safety considerations that apply.

4.4.3 Orbital Flight Medical Effects

On orbital flights of up to two weeks, the passengers and the flight crew may experience exposure to the more familiar and conventional effects of micro-g and threats of radiation exposure. The first effect of space sickness pertains. Micro-g does not pose a long-term exposure threat to the passengers but it may to the flight crew. Again, the time factor makes all the difference for the flight crew. Say the crew flies for two weeks every month so their total exposure time adds up to half a year every year. This total duration places the flight crews in the range for all the well-known effects of long-term exposure to micro-g: fluid shifts, bone demineralization, and particularly loss of muscle tone and muscle mass.

4.4.4 Radiation Exposure: The Special Hazard

Orbital flight also incurs the risk of exposure to radiation. There are two main risks: short-term exposure to high-dose radiation from a solar flare aka solar particle event with symptoms in the optic system such as cataracts (NASA STD-3001A, Vol. 1, p. 22) or long-term exposure to low-dose radiation from solar energetic particles (mainly protons) and galactic cosmic rays. The Recommended Practices suggests that it is interested only in hazards that may cause an immediate effect. Unfortunately, this omission from the Recommended Practices of a section on ionizing radiation misses a very important domain. OSHA and other safety agencies regulate radiation exposure for workers on Earth where the effects are almost always very long-term. This omission for crew appears to be more a symptom of the failure to distinguish between flight crew and passengers than a failure to understand the hazards of the space environment. Future regulations must consider not only the very long-term effects such as cancer but the more near- or intermediate-term effects such as metabolic impacts upon the hippocanthus and functional decrements to the optic nerves.

4.4.4 Two Sets of Exposure Limits?

There may be further differences between the flight crew and the passengers that bear further examination. The key point is that treating crew and passengers all the same—as "occupants"—will not facilitate that investigation or enhance human spaceflight safety. Future regulations must establish one set of parameters and limits for passengers and another set for professional crew.

4.5 FIFTH SYSTEMIC FINDING: Omission of Risk Management and Reliability Strategies

The Recommended Practices need to discuss the common approaches to risk management strategy and the distinctions among them as they apply to commercial crew spacecraft. Here are the key approaches for the *Recommended Practices* to consider in a systematic way:

1. Design for minimum risk,
2. Fail-safe,
3. Fail-operational,
4. Failure Tolerance (aka Fault-tolerant),
5. As Low as Reasonably Achievable (ALARA).

Unfortunately, the Recommended Practices do not use this terminology, which comprises the near-universal language of human spacecraft safety. These gradations of risk management do not arise as often or in the same ways in the aeronautical vehicles as they do in human spacecraft. Perhaps it is not surprising that an "editor" may have tried to make all prescriptive statements consistent in the subjunctive so as not to appear to dictate to the commercial space companies. This situation brings to mind Ralph Waldo Emerson's (1841, p. 8) famous dictum:

> A foolish consistency is the hobgoblin of little minds, adored by little statesmen and philosophers and divines. With consistency a great soul has simply nothing to do.

4.5.1 Design for Minimum Risk

The language used to describe the risk management and reliability methods for each of the above approaches must vary to correspond to the approaches themselves. The Recommended Practices mention the principle of *Design for Minimum Risk* in some sections, but not in all sections where it may apply. Indeed, *Design for Minimum Risk* is a reliability strategy that the spacecraft designer selects out of the menu of options above. Certainly, some technical or operational challenges are more amenable to *Design for Minimum Risk* than others, which standard or conventional practices reflect.

What is most distinctive about *Design for Minimum Risk* is that it applies almost universally where redundancy is not possible, where a serious failure probability may cause—in the antiseptic jargon of the reliability discipline— "loss of crew" or "loss of mission." One failure. That is what design for minimum risk seeks to prevent. Almost always, when stating design and performance expectations for a vehicle or system under Design for Minimum Risk, the modal verb auxiliary is *shall.* There are no "shoulds," no "mays," no good wishes, or no pleas for good performance in *Design for Minimum Risk*. For example, a model *Recommended Practice* might read:

> *The pressure vessel primary structure of the fuselage shall protect the vehicle from loss of breathable atmosphere under normal operating conditions. It shall withstand an impact from a micrometeoroid or particle of space debris larger than x mm to a probability of y.*

Please note that the statement of a probability of failure needs to specify the threat regime against which it protects. In this case, it is necessary to state the estimate of the threat (size of the micrometeoroid or space debris) for the probabilistic analysis to obtain traction. Therefore, writing the sections that apply to design for minimum risk in the subjunctive utterly subverts the meaning and intent of that section.

4.5.2 Fail-Safe Design

Although the *Recommended Practices* mention several scenarios that resemble the *fail-safe* approach, nowhere does it discuss it or when it is appropriate to apply it. *Fail-safe* is almost ubiquitous to many engineered systems as the most common means to ensure safety. *Fail-safe*[4] design has two common or generic meanings. One meaning characterizes an adjective:

> *Fail-safe describes a property of a system or portion of a system that reverts to a safe condition in the event of a failure or malfunction.*

A well-know example of this meaning of fail-safe describes a circuit breaker. If there is a current overload, the breaker trips to render the circuit into a condition safe from overload and possible melting of insulation or ignition of an electrical fire. The other meaning is a noun:

> *A fail-safe is a system or subsystem that activates or becomes operational in the event of a failure to ensure the continuation of a safe condition.*

A meaning of the noun that appears in the Recommended Practices would be that if the vehicle crew loses the ability to command a particular function on the vehicle, another part of the system, the "mission control" on the ground may provide the *fail-safe* of commanding that function.

Now, please consider how one might apply *should* or *shall* to either of the meanings of fail-safe. This application affords a test of which, if either modal verb auxiliary is appropriate or sufficient. Can one say: How about the "circuit breaker *should* serve as the fail-safe," or, "the circuit breaker *shall* serve as the fail-safe?" In fact, *fail-safe* is truly self-explanatory, so wouldn't "the circuit breaker serves as the fail-safe" enough, without any modal verb auxiliary? This point means that often it is appropriate and sufficient to simply state what a system or its parts does in terms of performance. In practice, if a human spacecraft hits a fail-safe mode, the most likely plan is to return to Earth or a safe port (as in docking to the ISS) as soon as possible. *Loss of mission* is highly preferable to *loss of crew.*

4.5.3 Fail-Operational

The Recommended Practices do not discuss the *Fail-Operational* approach. That omission is particularly unfortunate, because in actual practice, an astronaut crew conducts most operations in a fail-operational system.

Fail-operational refers to a risk management design approach to reliability in which a system fails, but the spacecraft can continue to operate nominally. There are many variants on the term *Fail-operational* such as fail-passive and *fail-soft.* Probably the most common understanding of *fail-operational* is to provide a complete level of redundancy to the most failure-prone safety-critical systems or subsystems. Fault tolerance is often another construct of *fail- operational*, but it has different implications for hardware and software. For hardware, the level of redundancy usually means a "like" redundancy of a second set of everything needed to meet the safety-critical requirement. For software and for some operations, fail-operational often means "unlike" redundancy with the ability to self-correct or to try a different way of solving the problem or avoiding the threat.

An example of this arose in the Northrop Grumman work on the Altair lunar lander. With only one multi-spectral analyzer for the life support system and one external thermal loop, the "minimal design" did not pass

[4] Some versions of Fail-safe drop the hyphen as "failsafe." Here it is hyphenated for consistency with fail-operational.

the reliability analysis. However, simply providing redundancy to the multispectral analyzer and the thermal loop (with double valves on each loop) raised the reliability to meet the NASA goal of 1/1000 probability of loss of crew and 1/500 probability of loss of mission.[5]

4.5.4 Failure Tolerance

Failure tolerance appears early in the Recommended Practices to discuss the preferred approach to preventing a potentially catastrophic failure. *Section 1.3.1 Failure Tolerance to Catastrophic Events* states two conditions or options:

a. *The system should control hazards that can lead to catastrophic events with no less than single failure tolerance.*

b. *When failure tolerance adds complexity that results in a decrease in overall system safety or when failure tolerance is not practical (e.g., it adds significant mass or volume), an equivalent level of safety should be achieved through* ***design for minimum risk.***

This pair of assertions is curious and almost self-contradictory. Counter-intuitively, it does not work to state "should do this, or as a last resort should do that." The first statement is unconditional and in the subjunctive; the system should control hazards with single failure tolerance or better. Please note what should be obvious: the first statement provides a subject, *the system*, and an active verb, *should control*. The use of *should* here is appropriate because it recommends a minimum level, but allows a higher level, and also leads to an alternative.

Unlike the first statement, the second statement in the conditional mood with two arguments: "*When* failure tolerance *adds* complexity that *results. . . .*" The solution for all this double conditionality is *design for minimum risk.* That also is well and good. However, design for minimum risk here is the final choice, the last option, the only way to prevent catastrophe. So, why is it in the subjunctive? The authors weasel-worded the sentence twice with conditional modifiers. Why don't those arguments provide sufficient cover-your-ass self-confidence to state, "The system ***shall*** achieve an equivalent level of safety through design for minimum risk?" Please recall from the section on design for minimum risk that the prescriptive form almost universally uses *shall.*

Please note also the elimination of the passive verb *should be achieved* and its replacement by the active verb *shall achieve*. Please note further that the passive verb form generally lacks a subject in the operative clause of the sentence –as it does here, so that it is not clear *what* achieves the equivalent level of safety. In the *active verb form, the operative clause provides a subject, "the system." The system achieves the equivalent level of safety.*

4.5.5 As Low as Reasonably Achievable (ALARA)

The conflating of the flight crew with their passengers so that the Recommended Practices refer to all as "occupants" appears to set up the omission of any mention of ionizing radiation as a threat to safety. Given this omission it is not surprising that there is no mention of ALARA. ALARA has been the standard approach to providing radiation protection for at least 50 years.

ALARA consists of an integrated system of astronomical monitoring, measuring exposure, construction of the spacecraft with shielding materials, and the provision of protective garments or enclosures. It is not necessary to go into detail about the vast field of radiation research and countermeasures, but it is useful to mention the most recent complete and integrated analysis for crew safety: NASA CxP-70024E Human-System Integration Requirements, Section 3.2.7 Ionizing Radiation, which is available on the NASA Technical Report Server.

5. Discussion

So, what are the uncited (absent from the Recommended Practices) government and industry standards that do apply to commercial spaceflight crew and passenger safety? The Recommended Practices recognized the NASA Commercial Crew requirements as a general template, but the Recommended Practices states "Such details may be better addressed in industry standards." As of this writing, industry standards in the sense of consensus documents do not exist. Certainly, some companies have written their own internal standards, but there has yet to be any effort to merge such standards between companies. That means, that the only available and operative standards are government standards, primarily from NASA.

5.1 Existing (NASA) Standards

For human-spacecraft integration, the current "gold standard" is NASA STD-3001A Volume 1 for Crew Health and STD-3001 Vol. 2 for Human Factors, Habitability, and Environmental Health. In combination with the Human Integration Design Handbook (NASA, 2010) they form the current universe of NASA requirements for astronaut health and safety. They

[5] Full Disclosure: The author was the Human Systems Integration, Life Support, and Thermal Systems lead for the Northrop Grumman pre-Phase A Lunar Lander Development Study in 2008. This study is still unpublished.

supplant the older Man-System Integration Standard (MSIS), NASA STD-3000, which included a wealth of illustrations. Although MSIS is no longer "operative," its illustrations can help the new reader to understand the text, even in the later standards.

5.2 Constellation Program Standards

For several subject areas, the Constellation Program documents (CxP) provide a detailed example of more general standards applied to a specific spaceflight program. Key among these documents are CxP-70017 Probabilistic Risk Assessment (PRA), CxP-70023 Design Specification for Natural Environments (DSNE), and CxP-70024E Human-System Integration Requirements. The PRA provides an instructive example of the practical application to a specific program that may be more useful than the more general handbooks and academic publications. The DSNE is an excellent, state of the art and science compendium of all the natural space environments that an exploration vehicle might encounter, including the entire Earth orbital environment where commercial human spacecraft are likely to fly for the foreseeable future. The HSIR represents the supreme accomplishment of the human factors and human system integration engineers and scientists in NASA and its contractor community. The HSIR is truly the best document of its kind.

One of the challenges of applying the HSIR is how to interpret and implement it in the design of a crewed spacecraft. The analysis and design for the Altair lunar lander provides an example of interpreting the NASA and company requirements together (Cohen, 2010, July [part 2]; Cohen, Houk, 2010, September [part 1]).

Two areas of focus for the commercial spaceflight operators will be to develop their own approaches to human-system integration (HSI) and to their concept of operations (ConOps). Ironically, the FAA published its own ConOps for commercial space transportation, but ironically, the Recommended Practices do not mention it. The NASA System Engineering Handbook (2017) offers outline formats for both HSI (Appendix R) and ConOps (Appendix S).

5.3 Launch, Landing, and Flight Modes

A key set of domains where the FAA has yet to focus its attention are the several modes of launch, landing, and flight. Although the *Recommended Practices* tends to paint all commercial missions with the same broad-brush strokes, in fact the differences in launch, flight, and landing modes may bring significant consequences and distinctions that the commercial space industry and the FAA both need to make explicit in the ways that they address them. TABLES 1 shows the distribution of orbital vs. suborbital flight trajectories, air launch vs. vertical pad launch, and piloted aerodynamic vs. parachute landing. At this time, the distinctions and diversity among the launch, orbital trajectory, re-entry, landing modes are sufficient to drive much complexity. It is conceivable and likely that as this growth industry innovates new ways to fly into space, the population of TABLE 1 will increase with more variation and considerations in safety conditions for the FAA to consider.

5.4 Additional Considerations

It is certain that as the commercial human spaceflight capability develops, operates, and expands that the spaceflight community and the FAA will learn about new concerns and considerations for crew spaceflight safety.

5.4.1 Commercial Payloads and Experiments

One area likely to attract attention would involve on-board, IVA commercial payloads. During the Space Shuttle, Spacelab, and ISS programs, third party payloads have experienced malfunctions and failures that potentially could have led to a safety hazard for the crew, mission, or vehicle. Fortunately, none of these occurrences resulted in an accident or loss of life.

FIGURE 29. Sierra Nevada Corp mockup of possible anticipated commercial and scientific payloads on board the Dream Chaser. Courtesy of Sierra Nevada Corp.

However, going forward, a reasonable follow-on to the Florida Institute of Technology's gap analysis and this essay would be a study of commercial payloads and the potential hazards to safety they may present. This study will become especially relevant when there is no Payload Operations Center or Mission Control "back room," with staff numbering in the hundreds who are monitoring the functioning of every subsystem and payload on board the spacecraft. FIGURE 29. shows a Sierra Nevada Corp. mockup of prospective payloads stacked together inside a Dream Chaser. The potential exists for unexpected interactions among these varied sources of electromagnetic interference, heat, off-gassing, static charging, vibration, and other environmental variants.

5.4.2 Private Destinations in Space

A further consideration for the FAA concerns what role they should play—if any—in regulating the destinations for commercial crew spacecraft such as private space stations or space hotels, and private Moon or Mars bases. This conjecture is not so far-fetched. The FAA regulates airports in the United States, with stringent requirements for take-offs, departures, approaches, and landing. The FAA also regulates the design flight control towers, runways, aircraft ramps, and aircraft boarding arrangements of all types. FIGURE 30 shows a Bigelow Aerospace Space Hotel in LEO with several commercial crew spacecraft.

FIGURE 30. Bigelow Aerospace space hotel with three SpaceX Dragon-type capsules. Two Dragons are docked to this space station, possibly as 'lifeboats" in case of emergency evacuation, while the other is on approach. Courtesy of Bigelow Aerospace.

Other private or commercial destinations may include private space stations, space settlements at Lagrange Points, or lunar surface bases. The idea of the FAA regulating take-off, approach, and landing at a lunar base may seem a little far-fetched at this time. Eventually, an international regulatory framework may emerge for such operations. Until that time, the FAA may be the only agency that is cognizant of these types of potential commercial spaceflight operations.

5.4.3 International Regulation?

According to Sgobbo and Kezirian (2016), the manufacturers and operators of commercial crew spacecraft would like to see a consistent—if not uniform—regulatory regime develop internationally for their vehicles. Much of this discussion focuses on the precedents and paradigms for regulation from maritime transport and commercial aviation. Certainly, if people develop commercial crew vehicles in countries other than the USA, this international dimension will come to the fore and become imperative.

At the conference session in which the author presented this paper, other presenters described how other countries are preparing to regulate commercial and private spaceflight. Under this scenario, in which other countries regulate spacecraft while the US remains paralyzed under the Congressional ban, when the FAA is finally freed to do its job, it will need to play catch-up with the rest of the spacefaring world. Thus, these well-intentioned delays could ultimately place US providers at a distinct disadvantage in the regulatory arena.

6. Conclusion

In writing the Recommended Practices, the FAA labored under a severe restriction to not use language that readers could construe as *regulatory*. That objective is very difficult achieve when dealing with questions of life safety that traditionally are the domains of *must, need to, shall, and will.* The FAA accomplished this goal, but at the price of creating an incomplete, often ambiguous, or unclear set of guidelines.

the FAA made a good choice to request an independent review of their Recommended Practices. The timing will be sensitive for the second edition that will flow from this review. For the first edition, five years ago, there was substantial uncertainty about whether the commercial cargo providers and the independent suborbital providers would ever fly people as passengers and tourists. Now, four years later, several of the commercial space companies have taken big steps toward flying commercial vehicles in space within the next year. So, this review is timely and appropriate.

In order for the second edition to be more successful than the first, the FAA will need to respond constructively to the five major findings of this review. The FAA needs to resolve its identity crisis and accept that any role in advocating or supporting safety demands that they state requirements in cases where the subjunctive is simply not appropriate, as in the implementation of design for minimum risk. In addition, the FAA must treat commercial space crews as their own category for occupational health and safety, distinct from passengers or tourists. Finally, the FAA needs to discuss risk management and reliability strategies in the language of that discipline and not try to soften it or take both sides of every option.

What is most important is that before undertaking the development of any regulations, the FAA must conduct a comprehensive study of all the commercial space companies' policies and practices for design, engineering, manufacturing, and operations. It will be equally important for the companies to publish this information ton the space community. No doubt some will raise objections that it is all *proprietary*. But this openness will be essential to enabling and assuring safety. Safety flows not from secrecy but from transparency.

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