Perspectives on Human-Rating

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The term 'human-rated' is typically used to differentiate the increased safety requirements imposed on crewed spacecraft relative to unmanned satellites, including the launch vehicle as an integrated element. At a fundamental level, human-rating attempts to ensure the vehicle(s) and mission 'accommodate, protect, and utilize' the crew to the maximum extent possible, while safeguarding both ground personnel and uninvolved public. This definition drives life support needs, risk mitigation strategies, and vehicle and operational functionality, among other design requirements. The end result can generally be reduced to a single metric – the ability to safely accomplish the mission objectives with an acceptably low probability for Loss of Crew (LOC). Although this overarching goal may be well agreed upon, the means for achieving human-rating remain the subject of debate. This paper presents an overview of published literature and various NASA documents governing human-rating, considers the relevance of analogies such as FAA airworthiness certification and housing certificates of occupancy, and offers a framework for further discussion of 'What does human-rating mean?' and 'How do we achieve it?'.

I. Introduction

SINCE the beginning of human spaceflight in the early 1960's, different efforts have been made to define 'human-rating' and prescribe how to 'human-rate' a spacecraft[1,2]. As a new fleet of commercial spacecraft are being developed, they bring with them varied designs with unique operations and a different way of doing business. Now more than ever, it is crucial to provide a clear definition of human-rating and how it can be implemented for varying spacecraft designs. Providing a standardized definition for human-rating will allow spacecraft developers to have some baseline guidance for determining if their spacecraft is considered human-rated, and also help federal regulators provide a foundation from which to develop necessary policies, standards and regulations regarding commercial human spaceflight.

Historically, human-rating was viewed as a methodology to ensure increased reliability of systems and protect them from failure. But as the systems became more complex and missions grew longer, there was a need to better understand what it means to have a 'human in the loop'. From its rich history of human spaceflight experience, NASA has produced several documents providing guidance on and requirements for human systems integration.

From the NASA documentation, the fundamental tenets underlying spacecraft human-rating can be summarized scentas protecting the crew and passengers from harm, accommodating their physiological needs, and utilizing the crew's capabilities to safely and effectively achieve the goals of the mission. This foundation remains a central theme throughout all program activities, from conceptual design to flight readiness certification and mission operations, with consideration given to sustainment, maintenance, upgrades, and ultimately system retirement. Though the main tenets and general definitions are mostly agreed upon, there are several alternative ways of defining human-rating that may be more useful in specific design situations. Various definitions and additional perspectives are examined in this paper.

In addition to the goal of establishing a standard definition of human-rating, the methods of ensuring and ultimately verifying that the human has been well-integrated into the system also need to be better understood and developed. Though NASA has developed a systematic requirement-based process for this purpose, considerations

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that are more applicable to a regulatory regime or more suited for commercial processes may also need to be explored. By looking at established processes and standards across analogous industries it may be possible to extract insights into different methods of implementation for the human-rating process.

The purpose of this paper is to begin assessing the current status of human-rating definition, and provide insights as to how the process of human-rating a spacecraft might be implemented and ultimately verified. By drawing on historical work and current practices in both aerospace and related-fields, different perspectives on the human-rating process can be considered, and it is also important to bear in mind how the resultant regulations might impact the nascent market of commercial human spaceflight.

II. Background – Human-Rating of US Spacecraft and Launch Vehicles

Human-rating (or its precursor "man-rating") is a term that originated in the mid-20th century to describe aircraft that were deemed safe for human operation and later used to differentiate between early rockets and those intended to carry astronauts to space for the first time in terms of increase reliability needs. Historically, spacecraft human-rating has focused primarily on crew safety; however, in recent decades, the term has come to encompass both safety and crew performance[1]. Overall, the high level goals of human-rating can be summarized as the need to accommodate, protect and utilize the flight crew; safeguard ground personnel; and ensure that uninvolved public are not subjected to unacceptable risk.

A. Mercury

Project Mercury, America's first manned spaceflight program, utilized a single-seat capsule built by the McDonnell Aircraft Company. The spacecraft was launched on top of a modified inter-continental ballistic missile—the Redstone rocket in the case of early suborbital flights, and the Atlas D for later orbital missions. While both missiles had a less than exemplary track record, they were favored for the accelerated Mercury program because of the significant experience base already associated with them[2] .

Both Redstone and Atlas D shared many broad design characteristics with their unmanned predecessors. However, both manned launch vehicles contained additional redundancy and instrumentation, and both were built to more conservative design margins; the structure of each rocket, for example, was built to withstand 1.5 times its expected structural load. If the rocket were to fail catastrophically, an integrated launch escape system was tasked with automatically separating the spacecraft from the launch vehicle.

Originally, the Mercury spacecraft design was intended to be fully-automated; the astronaut would fly as a passenger, not as a pilot. However, the astronauts strongly objected to this "spam-in-a-can" approach, and ultimately a small viewport and manual control system were added to the spacecraft. The 3-axis, manual control system proved extremely useful in later missions, allowing Gordon Cooper to control his Faith 7 spacecraft during reentry after his automatic stabilization and control systems were lost.

Organizational procedures were also utilized to help ensure astronaut safety. Both Redstone and Atlas were exposed to extensive formal reviews and significant ground and flight-testing prior to manned launches. In addition, spacecraft and launch vehicle were built using parts identified by a "Mercury stamp" to indicate the component had met stringent quality control inspections. Mercury astronauts also made a point of visiting NASA contractors so workers would associate a "face" with the vehicle they were building[2].

B. Gemini

Gemini was intended to bridge the gap between Mercury and Apollo, with missions designed to parse out the techniques and technologies required for rendezvous, docking, long-duration flight, and extra-vehicular activity (EVA). Once again, McDonnell Aircraft was chosen to build the spacecraft, which was launched on a modified Titan II missile. Like the Atlas and Redstone rockets before it, Titan II was originally developed for military applications, then later adapted for manned use. These modifications included the addition of redundant hydraulic, electrical, and flight control systems, and a 1.25 factor of safety for structural components. However, because of budget constraints, engine test firings were significantly curtailed to less than a fifth of what had originally been planned.

While the experience of Mercury certainly contributed to the design of Gemini, the structure of the Gemini spacecraft and location of its subsystems differed significantly from its Mercury predecessor. Due to the thrust limitations of the Mercury launch vehicle, the Mercury capsule incorporated integrated systems, attached in the manner of a "layer cake"[3]; while this significantly decreased weight, it made spacecraft testing and checkout extremely burdensome. If a subsystem failed during checkout, several overlapping subsystems had to be removed in order to fix the original flaw. In contrast, the Gemini spacecraft utilized a separate "service module" for modularized subsystems, which significantly expedited and improved verification and checkout. Due to budget constraints, quality assurance and reliability testing of the spacecraft were significantly curtailed, replaced instead with cheaper, enhanced qualification testing.

Unlike its programmatic predecessor, Gemini lacked an escape tower. Both astronauts were launched with ejection seats that were designed to separate the crew from the capsule during a launch vehicle emergency. This abort system methodology was chosen ostensibly to simplify and "modularize", but proved difficult to implement in practice; a malfunction during testing destroyed a test dummy[3]. Notably, ejection could be initiated either automatically or manually, a technique very much in line with the greater flight control responsibilities allotted to astronauts during Gemini. Manual abort control ended up salvaging the Gemini 6 mission: when a tower plug separated prematurely from the Titan II rocket prior to liftoff, but the astronauts elected to remain in their capsule despite mission rules that called for an ejection.

C. Apollo

The Apollo program safely landed 12 men on the moon between 1969 and 1972. Apollo lunar missions were unique in that the 3-man crew utilized two separate spacecraft: the Command Service Module (CSM), which served as primary crew quarters and Earth-ascent and entry vehicle, and the Lunar Module (LM), which landed two of the astronauts on the moon's surface and returned them to the lunar orbiting CSM. These two spacecraft were launched together on top of the Saturn series of rockets—the first rockets designed explicitly for manned use. Saturn IB rockets were utilized for low-earth orbit missions; Saturn V rockets were used primarily for lunar voyages. All three vehicles—CSM, LM, and launch vehicle—were required to meet applicable human-safety requirements.

Although the Saturn series of rockets allowed engineers to design with humans in mind from the start, this brought with it the disadvantage that a knowledge base for the rocket did not exist prior to the man-rating process. To validate the design while maintaining the pace necessary to meet Kennedy's lunar landing goal, engineers employed a technique known as "all-up-testing", in which every stage of the vehicle was flown on every launch. In this manner, flight experience for the upper stages could be obtained in the event the lower stages were successful[4].

While 3 crew members were killed in a launch-pad fire during the early days of Apollo, no lives were lost inflight, and only one mission was lost (Apollo 13) out of a total of 15 excursions.

D. Space Shuttle

Originally launched in 1981, the Space Shuttle consisted of three separate components: the crew-occupied, reusable orbiter; the external tank; and the twin-solid rocket boosters. Unlike prior U.S. space programs, the shuttle stack was never tested in an unmanned configuration; its first launch was manned. After the first four "developmental" flights, ejection seats were pinned down, then later removed.

The Space Shuttle was *never* considered a human-rated vehicle. According to a 1988 JSC Memo titled "Guidelines for Man Rating Space Systems", the space shuttle was "highly reliable", not man-rated[2]. A highly reliable system, such as the space shuttle, had no escape systems, and therefore placed more emphasis on mission success than mission safety.

In its 135-flight history, the Space Shuttle was the only NASA program to experience catastrophic accidents. In 1986, the space shuttle *Challenger* exploded soon after launch; and in 2003, *Columbia* disintegrated upon reentry.

E. International Space Station (ISS)

The first module of the International Space Station (ISS) was launched in 1998; by 2011, the ISS was 98% complete. Although over 30 crews have lived on ISS in the 12 years it has been operational, there is no evidence to suggest the ISS has ever been explicitly human-rated. Construction of ISS began prior to the creation of what is now NASA's governing human-rating document, 8705.2B, "*Human-Rating Requirements for Space Systems*". Moreover, human-rating typically applies to an integrated system throughout its mission duration. Therefore, when docked to the space shuttle (a non-human rated vehicle), ISS human-rating certification would likely have been negated by definition.

F. Undeveloped Programs—Orbital Space Plane and Constellation

Developed but never flown, NASA's Orbital Space Plane (OSP) was intended to serve as a crew return vehicle for the ISS. Budget cuts ended work on the program in 2002, but not before completion of a preliminary human-rating plan (HRP). This HRP would eventually come to serve as the basis for subsequent U.S. spacecraft human-rating methodologies (most notably, the Constellation and Commercial Crew

Programs). The OSP HRP developed the concept of human-rating as a requirements-based methodology, under which spacecraft are considered human-rated so long as they meet the requirements found in 8705.2 or its derivative (8705.2 governed OSP, 8705.2A regulated Constellation, and 8705.2B currently dictates Commercial Crew Program development). While 8705.2 has evolved over the years, its requirements have typically focused on crew safety and operability.

G. Future Work—Atlas V

The Atlas V Expendable Launch Vehicle (ELV), a direct descendant of the Mercury Atlas rocket, is expected to launch Boeing's CST-100 spacecraft, Blue Origin's New Shepard system, and Sierra Nevada Corporation's (SNC) Dream Chaser space vehicle in the coming years. According to United Launch Alliance (ULA), the company directly responsible for Atlas V development, the vehicle is expected to meet applicable 8705.2B human-rating requirements without major modifications[5]. While the Atlas V is described here to showcase current human-rating developments, it is important to note that the human-rating process ultimately refers to the entire integrated system (e.g. spacecraft, booster vehicle, ground systems, and crew), not to individual components such as the launch vehicle.

III. Current Direction of Human-Rating

With the retirement of the Space Shuttle Program and an emerging new commercial human spaceflight era, spaceflight is transitioning from a nearly exclusive government undertaking into a fledgling industry, much as the earlier transition was made to commercial communication satellites. As space transportation opens up to the general population, new guidelines have to be set to ensure the safety of the crew, passengers, and the uninvolved public. But as it is a developing market, the government also needs to be cautious with its oversight and not strangle the incipient industry with too many regulations. This calls for a review of the current practices and guidelines and reassessing their intended purposes for the needs of the commercial spaceflight market.

NASA documentation provides a foundation of understanding how to accommodate and utilize crew members in a space vehicle. The 50 year history of human spaceflight has provided insight to the allowable limits of human physiology in space, while operational guidelines can direct designers to human factors issues and considerations for how to achieve optimal crew performance. Safety aspects of human-rating are also currently captured in NASA's documentation and generally embedded in systems as design margins, reliability levels, component redundancy, etc. Additionally, ground safety and protection of the uninvolved public is covered by similarly defined range safety requirements. It is anticipated that the Federal Aviation Administration (FAA) will have regulatory oversight for passenger and crew safety in the non-NASA commercial domain, and thus, it is important to assess their current framework as to how human-rating regulations would be incorporated as well.

A. Current NASA Documentation

Commercial spacecraft en route to the International Space Station (ISS) are bound primarily by the requirements described in CCT-REQ-1130, "*ISS Crew Transportation and Services Requirements Document*"; SSP-50808, "*International Space Station (ISS) to Commercial Orbital Transportation Services (COTS) Interface Requirement Document (IRD)*"; and AFSPCMAN-91-710, "*Range Safety User Requirements*. While commercial crew programs are no longer programmatically directly bound to the original human-rating document, 8705.2B *("Human Rating Requirements for Space Systems"*), many of the requirements found in CCT-REQ-1130 replicate the requirements found in 8705.2B. All told, these documents collectively yield approximately 6,500 unique requirements.

NASA also provides a set of guidelines for accommodating humans in the spacecraft with their *Human Integration Design Handbook* (HIDH) (NASA/SP-2010-3407). This document provides a comprehensive look at the interior spacecraft design and layout considerations, and it describes standard ranges and design criteria to ensure crew comfort and allow for adequate human performance, hence, providing guidance for accommodating and utilizing the crew.

B. Current FAA Regulations

In 1926, President Calvin Coolidge signed the Air Commerce Act of 1926 to initiate federal regulation of aviation. Its main goals were to foster air commerce, designate and establish airways, establish, operate and maintain aids to air navigation, arrange for research and development for improving those aids, license pilots, issue airworthiness certificates, and investigate accidents. As aviation began to flourish and become a major commercial industry, the Federal Aviation Agency (later to become the Federal Aviation Administration in 1967) was formed in 1958 to provide for the safe and efficient use of national airspace[6].

Following the path of aviation, the Commercial Space Launch Amendments Act of 2004 established a distinct regulatory framework for private human spaceflight. As authorized by the Commercial Space Launch Act in Title 51 of the U.S. Code[7], the FAA license and regulates U.S. commercial space launch and reentry activity, as well as the operation of non-federal launch and reentry sites. The mission of the FAA's Office of Commercial Space Transportation (AST) is to ensure public health and safety, preserve property and protect U.S. national security and foreign policy interests during commercial launch and reentry operations. In addition, FAA/AST is directed to encourage, facilitate, and promote commercial space launches and reentries.

The current regulations for human spaceflight are codified in Chapter III of Title 14 in the Code of Federal Regulations. There are specific requirements for launch and re-entry licensing; safety and operations; financial responsibility of operators; as well as some limited guidance on crew qualifications, training, and vehicle accommodations for the crew[8]. The regulations at this time are in place to ensure the crew is safe enough to maintain operations of the vehicle. At this time, the FAA/AST is focused primarily on public rather than passenger safety. As the industry develops, standardization and requirements for interior accommodations will likely begin to mimic those found in the current FAA airworthiness certification process.

IV. Risk Analysis and LOC probability

As for any mode of transportation, some degree of risk will always accompany space travel. The goal is to control the risks to a programmatically or politically acceptable level. NASA derives Loss of Crew (LOC) likelihood using a statistically quantitative analysis technique known as Probabilistic Risk Analysis (PRA)[9]. With PRA, the probability that a certain hazardous event will takes place is propagated by the consequence of said event to determine the net uncorrected outcome. Summing these probabilities generates an overall LOC value.

NASA has stated that the next generation of commercial vehicles must meet an overall LOC of 1 in 270 (CCT-REQ-1130). This exceeds the space shuttle LOC (2 in 135) by a factor of four, but is only a quarter of what has been requested by the astronaut office (1 in 1000)[10]. In comparison, the probability of dying in a commercial aviation accident (1 in 3,000,000 hours flown), automobile accident (1 in 54,000,000 miles driven), or SCUBA diving accident (1 in 200,000 dives) is significantly smaller than any of the three probabilities listed above. And interestingly, in recent years, the probability of dying on Mount Everest has been virtually equivalent to the probability of dying in a space shuttle accident. However, it should be noted that the numerator in these comparisons is not consistent – sorties, time, distance – and this comparative metric must be considered when assessing overall risk. Furthermore, spacecraft LOC distributions have been evaluated on a per mission basis, as each in-flight, catastrophic event has resulted in total loss of crew (*Challenger*, 1986; *Columbia*, 2003). However, that is not to say that each LOC event necessitates a complete loss of crew; conceivably, there are scenarios in which only individual crew-members are lost, which is not typically taken into account. In such a situation, the classic (per mission) method used to calculate and analyze LOC distributions is not the same. The actual LOC distribution for shuttle, when analyzed on both a per mission and per crew member basis, however, yields similar values (the per mission LOC for shuttle was 2 in 135, or 0.015; the per person LOC for shuttle was 14 in 817, or 0.017).

These variations suggest that LOC values are unit dependent, and can conceivably be manipulated to meet requirements. As an exaggerated example, when viewed on a per mile basis, the percentage of fatalities for U.S. railways is greater than that for either shuttle or Soyuz. A summary of example fatality values for different forms of transportation is listed in **Error! Reference source not found.** as a means of comparison. As the commercial spaceflight industry moves forward, it may be important to consider how risk will be measured..

Transportation Data	Fatal Excursions	Total Excursions	Fatalities	Total Passengers	Total Miles (Millions)	Passenger• Miles (Millions)	Hours	Passenger• Hours
Shuttle	2	135	14	817	543	3,396	31,913	199,664
Soyuz	2	110	4	273	4,906	13,332	284,840	774,072
121 Aviation (U.S. 2009)	30	10,027,400	52	769,600,000	7,557	1,026,800	18,000,000	N/A
General Aviation (U.S. 2009)	275	N/A	478	N/A	N/A	N/A	20,826,000	N/A
Automotive (U.S. 2009)	30,797	N/A	24,474	209,618,386	2,953,501	N/A	N/A	N/A
Railway (U.S. 2009)	N/A	N/A	3	N/A	103	N/A	N/A	N/A
Commercial Crew	N/A	270	1	N/A	N/A	N/A	N/A	N/A

Analysis	Fatal Missions/Total Missions	Fatalities/Total Missions	Fatalities/Total Passengers	Fatalities/ Total Miles	Fatalities/ Total Passenger •Miles	Fatalities/ Total Hours	Fatalities/ Total Passenger •Hours
Shuttle	0.0148	0.1037	0.0171	0.02578	0.00412	0.00044	0.00007
Soyuz	0.0182	0.0364	0.0147	0.00082	0.00030	0.00001	0.00001
121 Aviation (U.S. 2009)	0.00000299	0.00000519	0.00000007	0.00688104	0.00005064	0.00000289	N/A
General Aviation (U.S. 2009)	N/A	N/A	N/A	N/A	N/A	0.00002295	N/A
Automotive (U.S. 2009)	N/A	N/A	0.0106	0.00000001	N/A	N/A	N/A
Railway (U.S. 2009)	N/A	N/A	N/A	0.02912621	N/A	N/A	N/A
Commercial Crew*	N/A	0.0037	N/A	N/A	N/A	N/A	N/A

Table 1: Fatality Data for Various Forms of Transportation[4] (*This value is from NASA CCT-REQ-1130 requirements)

V. Related Analogs

Analogs in other industries with similar environments and/or involving related human operations were also examined for additional consideration and insight. The purpose of looking at these analogs is to explore other perspectives that may shed light on how similar human-rating types of demands are implemented in different industries.

A. FAA Aircraft Airworthiness

Although aircraft and spacecraft share a somewhat common engineering lineage, spacecraft human-rating is significantly more difficult to assess and achieve. Spacecraft operate in an environment that is not fully characterized and challenging to duplicate for test purposes. As such, spacecraft face more "unknown unknowns" during their initial missions than their aircraft counterparts. Moreover, aircraft often undergo thousands of hours of flight tests prior to becoming operational; but due to the extreme costs associated with space launches, spacecraft are rarely afforded that luxury. In contrast, the space shuttle was classified as 'operational' after only 5 flights, a timeframe that would be inconceivable for most modern aircraft. Interestingly, the concept of adding humans to rockets came after unmanned designs had been used for other purposes, thus human-rating came later in the evolution. On the other end of the spectrum, aircraft essentially started out with pilots onboard but are now moving to the opposite challenge of certifying their use in unmanned operations.

Though the FAA does not currently provide guidelines for space passenger accommodation, as the industry develops, there will be a demand for passenger comfort and safety that should define best practices, guidelines, standards, and ultimately, policies. An analogous regulation process would be that of the FAA's airworthiness certificate for aircraft.

The FAA authorizes type-certified aircraft as "airworthy" with Standard Airworthiness Certificates (AC), which categorizes aircraft as normal, utility, acrobatic, commuter, transport, manned free balloon, or special class. To be considered airworthy, the aircraft must (1) conform to its type design, and (2) be in a condition for safe operation[11].

According to the FAA, "the standard airworthiness certificate remains valid as long as the aircraft meets its approved type design, is in a condition for safe operation and maintenance, preventative maintenance, and alterations are performed in accordance with 14 CFR parts 21 [Certification Procedures], 43 [Maintenance, Rebuilding & Alteration], and 91 [General Operating and Flight Rules][12]."

In addition to type classification, Airworthiness Standards for each aircraft type are detailed out in Subchapter C of Chapter I in the U.S. Code Title 14. The standards regulate the aircraft design from exterior to interior as well as its operations from take-off to landing. When these standards have been met along with numerous test flights conducted, an aircraft receives its airworthiness certification. As the commercial human spaceflight industry matures, it is anticipated that similar standards may need to be developed to promote passenger safety.

B. Housing Certificate of Occupancy

From a completely different perspective, housing codes within the U.S. are enforced and allocated with a Certificate of Occupancy before humans are allowed to inhabit the building. The certificate and the process of

[4]The table was generated by aggregating data from the following sources: http://www.bts.gov/publications/national_transportation_statistics/, http://www-nrd.nhtsa.dot.gov/Pubs, and historical Space Shuttle data from NASA.

obtaining it varies from state to state, but typically have a prescribed set of building codes that must be followed prior to obtaining certification.

For the United States, a Certificate of Occupancy is a document issued by local government agency or building department certifying a building's compliance with building codes and other laws, indicating a condition suitable for occupancy. The certificate is evidence (often the in the form of an accompanying building permit) that the structure complies with the plans and specifications that have been submitted to, and approved by the local authority.

There are 10 different types of building certificates. The list of considerations for constructing a new building is shown in Appendix A. To obtain a certificate of occupancy, a valid building permit is required which is proof that the building design and construction adhered to building codes as required by the local government agency. Building codes specify the use and classification of the building type as well as a set of standards for inhabitant safety (fire, egress) and basic comfort, design and construction quality, and construction safety.

C. Deep Sea Diving Operations

Deep Sea Diving Operations present somewhat similar challenges to human spaceflight in that the user is enclosed in a suit or habitat to protect the occupant from the external environment; respiration is provided by a specialized system; and failure of these systems or following the proper operations can lead to death. The analogy can be drawn to the use of the extravehicular mobility unit (EMU) for space walks and determining whether this system needs to be fully 'human-rated' to the extent of a space vehicle. With diving as with spaceflight, there are often checklists of instrument maintenance and operation guidelines that must be followed to ensure safe operations. While the operational analogies are clear and utilized by NASA for different purposes already, the safety protocols for diving may provide additional unique insight into human rating concerns for spacecraft. Saturation diving operations, in particular, can also be assessed in terms of crew accommodations and safety.

VI. Defining Safety and Operability Figures of Merit to Assess Human-Rating

While relevant analogies can provide insight for the definition of human-rating standards, the specific design process used for human-rating a space system must take many unique considerations into account. Often legacy practices and procedures are drawn from when designing a spacecraft, beginning at the conceptual phase. As such, engineers are likely to incorporate various degrees of redundancy and added factors of safety based on what prior designs included. In contrast, by starting with a 'blank sheet of paper', a 'minimally functional' design can be defined that consists of only exactly what is needed to accomplish a specific mission in terms of vehicle physics and crew physiology. This absolute minimum baseline represents a system that is technically flyable, assuming everything works as planned, but is obviously programmatically infeasible due to excessive risk. However, this design point can then be used to systematically assess what needs to be added in order to achieve desired degree of safety and/or additional operational goals beyond those required to just meet the basic mission objective.

To do so, it can be assumed initially that all required functions will be carried out as intended with 100% reliability to meet the mission requirements mandated by physics and physiology. This sets a non-negotiable baseline or lower limit of what is needed to conduct the mission and can be considered the minimum functionality design point. The next step is to begin addressing the potential for loss of a given function (hazard) and its impact to the design (outcome) that correlates criticality with an uncorrected functional loss. Outcome criticality (or severity) can be denoted using various quantitative schemes, but is essentially centered on the following hierarchal scheme: Loss of Crew (LOC), Loss of Vehicle (LOV), Loss of Mission (LOM), or Degradation of Capability. A probability analysis is then used to predict likelihood of a critical failure occurring.

Incorporating the severity and likelihood results into the design lays the groundwork for defining the detailed system requirements that, in addition to meeting all functional needs, must now take into account appropriate risk mitigation strategies for critical failure modes. All add-backs that can be incorporated as a result can be categorized as either making the spacecraft 'safer' or more 'operable'. By defining non-dimensional indices that capture these relative effectiveness of these two variables, it is conceivable to establish Figures of Merit that provide ranking information in terms of the fundamental human rating tenets: to protect and utilize the crew. This general process described in simplified terms above, in conjunction with determining a programmatically acceptable level of risk, therefore offers a method that can be used to help human-rate a space system.

VII. Summary

From the various perspectives reviewed here, as well as assessment of current space system design requirements, a general definition of human-rating can be summarized follows: a human-rated spacecraft must (1) accommodate the physiological needs of the crew and passengers, (2) protect them from harm, and (3) utilize the crew's capabilities to safely and effectively achieve the goals of the mission. This definition has been garnered from government documentation and insight from other relevant analogs, but may not cover all aspects that should be considered. Minimizing risk to the uninvolved public must also be considered, and is currently mainly captured in range safety requirements. As a starting point, it is proposed to establish a commonly agreed upon definition of human-rating throughout the commercial space industry, and from there determine a suitable process for verifying that each space vehicle carrying human crew to orbit or on a suborbital trajectory, can be uniformly certified as human-rated.

Two options for implementation become evident from our review: 1) an outcome-determined verification or 2) a requirements-driven verification. In the first instance, there is minimal direct government oversight and regulation throughout the design process and the certification comes by test and operation of the final product. In the second, the government prescribes requirements and oversees the verification process from conceptual implementation through final certification. Table 2 categorizes the three tenets of human rating and suggests examples of different approaches by which they can be characterized or measured as a starting point for future discussion.

Human-Rating Implementation Approaches	
Safety	Design Factors of Safety
	Reliablity
	Failure Tolerance
	System Health Monitoring
	Emergency Detection
	Crew Escape
Operability	Effects of Human Interaction w/ System
Accommodation	Effects of Environment Caused by Human Presence
All	Design Requirements
	Test and Verification

Table 2. Possible human-rating implementation approaches and which of the three human-rating tenets it covers.

VIII. Future Work

As the need for commercial space passenger and crew safety grows, future work should include summarizing stakeholder positions regarding what should or should not be considered in the definition of human-rating criteria. In addition, a more thorough investigation is needed to compare and contrast the goals and needs of NASA versus those of the commercial spaceflight industry in terms of human-rating certification.

Eventually, it would benefit the industry if terminology is standardized for human-rating certification and defining how to implement and evaluate human-rating between spacecraft designs follows common practice. As the commercial industry develops, it will rely on guidelines and best practices initially, then as it matures, the process will evolve into standards, and ultimately policies that are appropriately regulated to ensure safety and allow the industry to thrive.

Appendix

	International Building Code (Certificate of Human Occupancy) IBC 2009	
Chap 4	Special Detailed Requirements Based on Use and Occupancy	Provisions for special uses and occupancies
Chap 5	General Building Heights and Areas	Controls the height and area of structures hereafter erected and additions to existing structures
Chap 6	Types of Construction	Control classification of buildings as to type of construction
Chap 7	Fire and Smoke Protection Features	Govern the materials, systems and assemblies used for structural fire resistance and fire-resistance-rated construction separation of adjacent spaces to safeguard against the spread of fire and smoke within a building and the spread of fire to or from buildings
Chap 8	Interior Finishes	Govern use of materials used as interior finishes, trim, and decorative materials
Chap 9	Fire Protection Systems	Specify where fire protection systems are required and shall apply to the design, installation and operation of the fire protection systems

Chap 10	Means of Egress	Requires buildings or portions thereof to provide a means of egress; controls design, construction, and arrangement and maintenance of means of egress and its components
Chap 11	Accessibility	Control the design and construction of facilities for accessibility to physically disabled persons
Chap 12	Interior Environment	Govern ventilation, temperature control, lighting, yards and courts, sound transmission, room dimensions, surrounding materials and rodent proofing associated with the interior spaces of buildings
Chap 13	Energy Efficiency	Governs the design and construction of buildings for energy efficiency
Chap 14	Exterior Walls	Establish the minimum requirements for exterior walls; exterior wall coverings; exterior wall openings; exterior windows and doors; architectural trim; balconies and similar projections; and bay and oriel windows
Chap 15	Roof Assemblies and Rooftop Structures	Govern design, materials, construction and quality of roof assemblies, and rooftop structures
Chap 16	Structural Design	Govern structural design of buildings, structures and portions thereof
Chap 17	Structural Tests and Special Inspections	Govern quality, workmanship and requirements for materials covered; materials of construction and tests shall conform to the applicable standards listed in this code
Chap 18	Soils and Foundations	Building and foundation provisions
Chap 19	Concrete	Govern materials, quality control, design and construction of concrete used in structures
Chap 20	Aluminum	Govern the quality, design, fabrication and erection of aluminum
Chap 21	Masonry	Govern the quality, design, fabrication and erection of masonry
Chap 22	Steel	Govern the quality, design, fabrication and erection of steel
Chap 23	Wood	Govern the quality, design, fabrication and erection of wood
Chap 24	Glass and Glazing	Govern the quality, design, fabrication and erection of glass and glazing
Chap 25	Gypsum Board and Plaster	Govern the quality, design, fabrication and erection of gypsum board and plaster
Chap 26	Plastic	Govern the materials, design, application, construction and installation of interior plastics
Chap 27	Electrical	Govern the electrical components, equipment and systems used in building and structures
Chap 28	Mechanical Systems	Mechanical appliances, equipment and systems shall be constructed, installed and maintained in accordance with the International Mechanical Code and Fuel Gas Code
Chap 29	Plumbing Systems	Govern the erection, installation, alteration, repairs, relocation, replacement, addition to, use or maintenance of plumbing equipment and systems (also see International Plumbing Code)
Chap 30	Elevators and Conveying Systems	Governs the design, construction, installation, alteration and repair of elevators and conveying systems and their components
Chap 31	Special Construction	Govern special building construction including membrane structures, temporary structures, pedestrian walkways and tunnels, automatic vehicular gates, awnings and canopies, marquees, signs, and towers and antennas
Chap 32	Encroachments into the Public Right-of-Way	Govern the encroachment of structures into public right-of-way
Chap 33	Safeguard During Construction	Govern the safety during construction and the protection of adjacent public and private properties
Chap 34	Existing Structures	Control the alteration, repair, addition and change of occupancy of existing structures

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