Spacecraft Human-Rating: Historical Overview and Implementation Considerations

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Abstract—**The fundamental tenets of a human-rated space system are to accommodate the needs of the crew, effectively utilize their capabilities to accomplish the mission objectives, and protect the crewmembers, as well as ground teams and the uninvolved public, from hazardous events. The concept of human-rating (previously referred to as man-rating) was originally primarily aimed at improving the reliability of launch vehicles for human use and increasing safety through the addition of escape/abort systems. The earliest use of this term found in the aerospace literature was in reference to the X-series experimental rocket planes. Later sources began including 'human in the loop' design aspects driven by ergonomics and human factors, which essentially extended the application to explicitly address crew utilization. Accommodating basic human needs in the hostile environment of space is primarily achieved by incorporation of a life support system. Beyond this basic provision, however, human factors and related medical considerations can also be used to improve overall health and performance of the crew. Throughout the years, the human-rating process itself evolved from providing general guidelines to being mandated as a set of prescribed requirements. Considered collectively, the ultimate goal is to help ensure safety and mission success through proper space system design and operations. This paper provides a brief historical overview of human-rating and considerations for its implementation throughout all phases of spacecraft design and operations.**

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1. INTRODUCTION

Human-rating is a term that has evolved since the beginning of human spaceflight [1,2,3,4,5,6]. While various forms of spacecraft design ratings and qualifications were being used early on, the first appearance of the specific phrase 'human-rating' itself that we found in the spacecraft design literature was from the early 1990's. Several variations of the term, however, such as 'man-rating', or 'highly reliable' systems, had been used previously to qualify space hardware developed for manned use or occupation.

The definition of 'human-rating' and how it is achieved can pose a potential source of confusion and concern to those developing new human space vehicles. The goal of this paper is to provide some historical context regarding how 'human-rating' came into being and trace its evolution from early guidelines to its current definition as a set of requirements. It also provides insight into various ways that the human-rating process is incorporated by the aerospace industry to help ensure safe and successful human space missions.

A. Evolution of Human-Rating

Human-rating (or it's functionally equivalent precursor, 'man-rating') is a phrase that originated in the mid-20th century to describe hardware developed specifically for manned use or occupation. The first vehicles to be human-rated in this context were the X-series of experimental rocket planes [3,7]. For this reason, the term 'human-rating' is most commonly associated in the literature with aircraft and spacecraft.

Originally, human-rating focused predominately on crew safety. The unmanned launch vehicles of the early space age were deemed too unreliable for safe human use, successfully reaching orbit less than 80% of the time [2,8,9]. To improve the likelihood of crew survival and mission success, redundancy began to be added to critical systems, reliability of components and subsystems was increased, and launch escape systems were developed [2,10,11]. These processes eventually came to be synonymous with safety aspects of human-rating.

As Mercury and Gemini evolved into Apollo and Skylab, human-rating began to focus on improvements to operability in addition to the focus on safety. As noted in a 1988 NASA document, 'The human rating process for the Mercury, Gemini, and Apollo Programs was centered on human safety. The Skylab and Shuttle Programs added to this an emphasis on human performance and health management [12].

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These additions, however, did little to provide verifiable human-rating practices. For the better part of the 20th century, human-rated was essentially applied to any system that could transport and/or support humans in space [13], rather than to specific vehicle or system capabilities or safety criteria. For example, no human-rating document or standard defined exactly 'how safe was safe enough' (or how operable was 'operable enough').

In 1988, a set of guidelines produced at the Johnson Space Center (JSC) attempted to bring clarity to the term by defining a human-rated system as one that required an escape system or safe haven. Based on this definition, the Space Shuttle was not considered by the JSC group to be human-rated; rather it was deemed "Highly Reliable" [14]. It wasn't until 1992 that human-rating began to take its current role as a requirements-based methodology. That year, NASA formed a committee to develop a set of human-rating requirements [12], which eventually evolved into JSC 28354 and ultimately NASA NPR 8705.2, the agency's "Human-Rating Requirements for Space Systems" and its current governing parent document for human-rating space systems. Interestingly, an evolution from 'guidelines' to 'guidelines and requirements' to just 'requirements' can also be seen throughout this time, as is reflected in the various document titles summarized later in Table 2 below.

B. Fundamental Tenets: Accommodate, Utilize, and Protect

NASA's "Human-Rating Requirements for Space Systems" document (NASA NPR 8705.2B) defines a human-rated system as one that 'accommodates human needs, effectively utilizes human capabilities, controls hazards and manages safety risk associated with human spaceflight, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations' [15]. In addition to protecting the crew members onboard the spacecraft (and eventually passengers as well) a human-rated system must also attempt to minimize any detrimental effects to any ground crews and the uninvolved public [16].

From this framework, three fundamental tenets of human-rating can be summarized as:

1. <u>accommodate</u> the physiological needs of the crew - *what the vehicle provides to support the humans, beginning with life support and extending to human factors/ergonomics*

2. <u>utilize</u> their capabilities effectively to accomplish the mission objectives - *what the humans can operate to support the mission, including optimization of human-machine interfaces*

3. <u>protect</u> the crewmembers (including passengers), as well as ground teams and the uninvolved public, from hazardous events - *addresses crew, vehicle and range safety considerations*

The evolution of these three basic human-rating tenets - *protecting, accommodating, and utilizing* – effectively spans the history of the U.S. spacecraft programs. Furthermore, while human-rating was originally associated solely with vehicle design, a shift occurred to recognize the programmatic implications of a human-rated designation and how it encompasses organizational practices as well. (See FAA Certification/Licensing regime and NASA Human-rating Certification) [17]. This reflects a transition from 'man-rating' of a vehicle to a broader concept of 'human-rating' a space system.

It is important to note that these tenets overlap to a certain degree and also introduce reciprocal impacts to each other. For example, if the crew members are not effectively accommodated by the vehicle, safety concerns might be introduced due to potential degradation of their performance (utilization). Additionally, the distinction between how a spacecraft accommodates or utilizes a crew member is often blurred. Therefore, a broad categorical definition for these two terms can be summarized as 'accommodate' being considered 'what the vehicle can provide for the crew,' while 'utilize' being defined as 'what the crew can provide to the operation of the vehicle.' The safety implications of 'protect' are usually more clearly understood.

2. ACCOMMODATING HUMANS IN THE SPACE ENVIRONMENT

While early human-rating of space systems often focused on the safety and reliability of the launch vehicle, the basic physiological needs of the human were considered by necessity as well, even if they were not explicitly identified as part of the human-rating process. The spaceflight environment presents several challenges to human life which must be addressed as part of spacecraft design. The natural hazards to life and health in orbital spaceflight fall into five general categories as follows:

1) Lack of Atmosphere (vacuum)
2) Thermal Extremes
3) Radiation
4) Micro-Meteoroids and Orbital Debris (MMOD)
5) Microgravity

In addition to these space environmental factors, there can also be induced environment issues in the spacecraft itself, where hazards to the crew exist such as noise and vibration, acceleration during launch, elevated CO_2 levels, circadian rhythm disruption, or inadvertent exposure to toxic propellants and coolants, and are all potentially detrimental to health. Accommodation of the crew into a spacecraft, must, therefore, focus on hardware requirements for keeping the crew alive and healthy through all phases and potential contingency scenarios of the mission.

Accommodation of humans in the extreme environment of space has its beginnings rooted throughout early aviation history. In the late 19th century high altitude balloon flights were being conducted for both research and exploration. In that timeframe, scientists and engineers began to realize that there were limits of temperature and pressure associated with the high-altitude environment that the human body could endure. Recognition of these limitations was reinforced as several pilots lost their lives due to lack of oxygen (hypoxia) and exposure to extreme cold as they reached the edges of the atmosphere. Two of the earliest documented fatalities reported to have been caused by a lack of adequate oxygen at altitude occurred in 1875 during a flight made by three Frenchmen: Croce-Spinelli, Sivel and Tissandier – two of whom died due to hypoxia after having reached 28,000 feet [18]. A second fatal incident occurred when Captain Hawthorne C. Grey died of hypoxia in 1927 while setting a new altitude record for the U.S. [19]. Fatal incidents such as these led to a growing demonstrated need for providing thermal control and an adequate supply of oxygen in this environment, which might be considered early adoption of a safety- and/or accommodation-driven design solution.

With the advent of World War I and, in particular, in the World War II era, heavier-than-air flight began a new pursuit of increasing speed and performance, which culminated in the eventual space race of the 1960's. Each step of the way revealed new limitations of the human body, but also brought new insights into how appropriate hardware design and technology could overcome these adversities and challenges.

In this general timeframe, aircraft development also started to gain traction from strategic uses during World War I. The vehicles were still quite primitive at the time and were mostly used for reconnaissance missions, but even at the relatively low altitudes in which they operated, it became obvious that supplemental oxygen was beneficial to pilot performance. Then, as aircraft and pilots began to push the altitude barriers following World War II, supplemental oxygen quickly became a design necessity [20]. As military aircraft continued to advance with increasing performance and complexity, oxygen delivery systems became even more sophisticated and were also extended to include passenger emergency availability in addition to the flight crew. The need for g-suits also became apparent for pilots.

Besides the lack of adequate oxygen and pressure, a number of other environmental factors are detrimental to human life and health. A major concern during early spaceflights included the impacts of acceleration, both from hyper-gravity exposure as well as weightlessness and deceleration on reentry and landing. Based on extrapolation of limited data from animal experiments conducted on the V-2 and Aerobee rockets, including peripherally-related ground studies, the anticipated consequences of weightlessness were hypothesized to include disorientation, hallucinations, and psychological adjustment failures. Additionally, doctors and scientists for the Mercury project worried about the combined stresses arising from noise, launch, and reentry tolerance, toxic hazards in the spacecraft, and finally ambient space radiation [21].

Accommodation of the crew for all these factors and others still remains a critical task for spacecraft designers. As part of the evolution of the definition of human-rating, Zupp (1995) noted that following each major space program, additional knowledge about space medicine was acquired. Project Mercury introduced issues of space motion sickness, vascular fluid shifts, hematopoietic abnormalities, and postflight gravitational intolerance, while the Gemini Project revealed the cardiovascular, hematological, and musculoskeletal changes arising from increasing spaceflight durations, and the Skylab program brought new studies on habitability and additional problems such as bone loss stemming from long-duration physiological adaptation [12].

Today's nascent commercial human spaceflight industry is ushering in a new era of space medicine where the anthropometric range and health issues of prospective spaceflight participants do not fit the above average 'fighter pilot model' of health and fitness that that define career astronauts. Many of the anticipated participants are much older, and will have a variety of age-related illnesses and health challenges. Research is currently underway to better understand the potential impacts of the space environment on this new class of adventure-seekers [22].

Throughout the progression of human space exploration, various documents were assembled to capture a basic understanding of the flight crew's physiological needs and associated medical concerns as shown in Table 1. A composite of these were eventually aggregated into the Man-Systems Integration Standard (MSIS), which itself references over 400 different publications and reports [23].

3. Human Factors and Crew Safety in Spacecraft Design

As human space missions increase in complexity in terms of hardware interfaces, anticipated mission capabilities, and longer durations, the human element becomes more relevant and critical regarding their expected roles in executing the mission goals. Some examples of extensive crew utilization include custom satellite deployment and repair, extravehicular activities (EVAs), and detailed scientific payload operations. Even more pressing demands for crew participation can occur during contingency, abort or emergency scenarios. In these time-critical instances, it is becomes exceedingly important to have the spacecraft designed appropriately to optimize the crew's performance to ensure their safety and mission success.

The term 'performance' can be defined as a two-step process: to think and to act [24] (or variations such as see-think-decide-do). The surrounding environment exerts a major influence on the ability for the human operator to think or to act, thus understanding the implications of certain design choices greatly impacts the crew's overall performance. Historically, this field of study falls under the umbrella of 'human factors' or 'human engineering'. These disciplines gained traction during World War II, where the practical needs of pilots and their ability to operate the vehicle was being out-paced by high performance designs. To address this, engineers had to determine better ways of designing the system for human interaction to reduce growing pilot mortality rates [25]. Additionally, much of this early aviation work produced large amounts of data on anthropometrics and ergonomics needed to characterize human body sizes and capabilities. This database was eventually used to define space program design requirements [26].

Accommodating and utilizing the crew are often two aspects of spacecraft design that are inextricably linked. For example, poor air revitalization and build-up of CO_2 has been correlated to slower cognitive performance [27]. One way to view this separation between accommodation and utilization is to think in terms of inputs and outputs to the crew. In this context, accommodations can be thought of as aspects of the spacecraft design that ensure the health and productivity of the crew (human 'inputs' from the vehicle), while crew utilization represents the overall performance achieved by the crew with the given accommodations (human 'outputs' supporting the mission). A list of key documents pertaining to historical and current crew accommodation and utilization definition is summarized in Table 1.

Table 1. Key crew utilization and accommodation literature and documentation

Document Number	Document Title	Date	Comments
MSFC-STD-512A	Man/System Requirement for Weightless Environments Airesearch	1976	Superseded by MSIS
JSC-07387B	Crew Station Specifications	1982	Superseded by MSIS
NASA STD-3000 (Vol I, II)	Man-Systems Integration Standard (MSIS)	1987	Superseded by MSIS Rev B
NASA STD-3000 Rev B (Vol I, II)	Man-Systems Integration Standard (MSIS)	1995	Superseded by NASA STD-3001
NASA STD-3001 Vol I	Crew Health	2007	Current practice
NASA STD-3001 Vol II	Human Factors and Habitability	2011	Current practice
NASA/ SP 2010-3407	Human Integration Design Handbook (HIDH)	2010	Current practice

4. PROTECTING THE CREW AND THE UNINVOLVED PUBLIC

Crew safety has been an essential design driver of human spacecraft development since the dawn of the space age. An early report summarized the then state-of-the-art approach to man-rating launch vehicles and rocket aircraft [1]. This report addressed emergency considerations, design aspects, quality assurance, and operations for programs including the X-15, Mercury-Redstone, Mercury-Atlas, Gemini-Titan II, and Dyna-Soar-Titan III vehicles, discussing significant aspects of man-rating as they have were applied to these projects. In reviewing the efforts at that time, a definition of 'man-rating' was offered as a 'unifying pattern upon which to build such a summary would be manned safety and vehicle reliability,' which essentially maps to today's role of Safety and Mission Assurance.

From this early era, methods of human-rating have evolved into current practices described as follows. Addition of redundancy, factors of safety, and design margins; as well as improved reliability from quality assurance, testing and verification, have all generally served to increase the safety of human spacecraft over the last 50+ years. Of the 290 manned launches from the U.S. and Soviet Union/Russia Space Programs between 1961 and 2012, only 4 have resulted in catastrophic (i.e., fatal) in flight accidents, amounting to a success rate of over 98% [28].

Probabilistic models are frequently used to derive a single metric that designates an overall assessment of safety and mission assurance. Outcome criticality (or severity) ranking can be denoted using various quantitative terms, 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 [29].

From a safety perspective, estimated LOC probability is the metric of greatest concern. This value is not a static outcome, however. As the design and/or operations evolve throughout a program's lifetime, the LOC probability analysis can be updated to incorporate new information. For example, mean probabilistic predictions for Loss of Crew/Vehicle (LOC/V) for the shuttle program ranged from 1:10 to 1:90 across missions from STS-1 to STS-133 as hardware and operational improvements were added [29]. Predictions also varied by time of analysis between 1987 (1:70) to 1998 (1:234) to 2010 (1:90) as methods used to predict the outcome evolved [29]. Franzini and Fragola (2011) provide historical perspective on human-rating that discusses paradigm changes from Mercury to Saturn and speculates on potential risks for future programs [6].

An overarching question in this context becomes 'How safe is safe enough?' The current acceptable risk target defined for NASA's Commercial Crew Program (NASA CCT-REQ-1130, requirement 3.2.1.3) states that the overall LOC probability distribution for an ISS mission shall have a mean value no greater than 1 in 270, and the LOC probability distribution for the combined ascent and entry phases of an International Space Station (ISS) mission shall have a mean LOC value of no greater than 1 in 500. This requirement applies to vehicles carrying NASA astronauts and/or for crews visiting the ISS. For non-NASA missions, the FAA has established safety regulations governing commercial space transportation [30].

Beyond addressing the needs of onboard crew and eventually passengers, safety of ground personnel and uninvolved public must also be ensured. As such, space launches from the Eastern and Western Test Ranges must also meet the requirements found in AFSPCMAN-91-710, “Range Safety User Requirements” [16]. These requirements cover generic worker safety for ground personnel and take protection of the uninvolved public into account through specific downrange safety provisions. Similar requirements have been put in place by the FAA for commercial launches as defined by the FAA’s Safety Approval Guide [30]. A chronological flow of some key historical and current human-rating documentation, mainly pertaining to safety concerns, is summarized in Table 2.

Table 2. Key human-rating literature and documentation

Document Number	Document Title	Date	Comments
Early Man-Rating Documentation and Guidelines			
NASA 410-24-13-1	Launch Vehicle Man-Rating	1963	Early Considerations for man-rating of launch vehicles
NHB 5300.4 (1D-2)	Safety, Reliability, Maintainability and Quality Provisions for the Space Shuttle Program	1979	
JSC-23211	Guidelines for Man Rating Space Systems	1988	Cohesive study of the man-rating process resulting in general guidelines
Transitioning from Man-Rating Guidelines to Human-Rating Requirements			
JSC-28354	Human-Rating Requirements	1998	JSC document from which 8705.2/A/B and 1130 were derived
NPG 8705.2	Human-Rating Requirements and Guidelines for Space Flight Systems	2003-2008	NASA HQ governing document for human-rating of NASA space systems.
NPR 8705.2A	Human-Rating Requirements for Space Systems	2005-2010	Evolution of 8705.2
NPR 8705.2B	Human-Rating Requirements for Space Systems (w/ change 3)	2008-2016	Evolution of 8705.2.A
NASA Commercial Crew Program Human-Rating Requirements (1100 series)			
NASA CCT-1001	Commercial Human-Rating Plan (Draft)	2010	Allocates commercial program responsibilities
CCT-PLN-1100	Commercial Crew Transportation Plan	2011	Certification to transport NASA/NASA-sponsored crew members
CCT-DRM-1110	Commercial Crew Transportation System Design Goals	2011	Reference missions to transport humans to/from ISS & LEO destinations
CCT-PLN-1120	Crew Transportation Technical Management Processes Draft	2011	Management processes for commercial crew
NASA CCT-REQ-1130	International Space Station (ISS) Crew Transportation Certification and Services Requirements Document	2011	NASA ISS crew transport certification and service requirements
CCT-STD-1140	Commercial Crew Transportation Evaluation of Technical Standards	2011	Technical, safety, and crew health & medical processes
CCT-STD-1150	Commercial Crew Transportation Operations Standards	2011	Establishes the ground and flight operations processes
Other Important Human-Rating Documents			
AFSPCMAN-91-710	Range Safety User Requirements	2004	Serves to protect ground personnel and range; preceded by EWR 127-1, “Eastern and Western Range Safety Requirements
NASA SSP-50808	ISS To Commercial Orbital Transportation Services (COTS) IRD	2007	Serves to protect ISS assets
N/A	SAFETY APPROVAL Guide for Applicants Version 1.0, Federal Aviation Administration Office of Commercial Space Transportation	2009	Pertains to commercial spacecraft launch and re-entry

5. SUMMARY

Ultimately, human-rating is as much a design philosophy as a design process. Whether the end qualification results from a requirements-based process or an outcome-based product assessment, or whether it leads to certification or licensing, the intent of human-rating is to protect the crew and ground personnel, including the uninvolved public, as well as to accommodate and utilize the crew in the most efficient way practical to meet the mission objectives.

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BIOGRAPHIES

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