NASA/TM-2014-217383

Defining NASA Risk Guidelines for Capsule-based Spacecraft Occupant Injuries Resulting from Launch, Abort, and Landing

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January 2014

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ACRONYMS

AIS	Abbreviated Injury Scale
ATLS	advanced trauma life support
EOM	end of mission
IS	injury severity
NASA	National Aeronautics and Space Administration
NASCAR	National Association for Stock Car Auto Racing
ORIS	Operationally Relevant Injury Scale
PRA	probability risk assessment
RFS	return to flight status
SAR	search and rescue
SE	self-egress
USAF	U.S. Air Force

ABSTRACT

A novel approach has been developed to define acceptable risk guidelines for human spaceflight injuries occurring during dynamic phases of flight (launch, abort, and landing). These risk guidelines are a driver for both vehicle and mission design, which in turn drive cost and schedule. The approach outlined in this document was based on three specific inputs. First, an Operationally Relevant Injury Scale was developed to categorize injuries within the framework of the spaceflight environment. Second, a systematic consideration of injury risk in other analogous programs and historic space programs was gathered for a pragmatic examination of realistic injury probabilities. Third, estimated Orion landing types and probabilities were determined along with the type of tasks crewmembers would be expected to perform in each type of situation to ensure mission success. These landing scenarios helped to define the range of injuries expected for capsule-based spaceflight. Considering each of these inputs, a panel of experts convened to define the absolute highest level of injury allowable that still achieved mission success. Once this level was defined, the panel began buying-down the risk with other considerations: ethical, medical, political, and programmatic. The results of this effort led to a Definition of Acceptable Risk for space-capsule landings that may be used to help set new standards to protect crews during dynamic phases of flight.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) needs to define acceptable risk guidelines for human spaceflight for injuries that occur during dynamic phases of flight (launch, abort, and landing). These risk guidelines are a driver for both vehicle and mission design, which in turn drive cost and schedule. While zero injuries would and should be the ultimate goal, from a probabilistic risk assessment standpoint the risk can never be zero. Reducing the risk to near zero injuries would entail enormous resources in terms of time, money, design, and materials, essentially rendering human spaceflight impossible to achieve.

Development of a framework for risk guidelines began with defining an Operationally Relevant Injury Scale (ORIS). Systematic consideration was given to injury risk in other similar programs, and historical probabilities of injury occurrence and type in spaceflight. Identification of the mission-related crew tasks and related probabilities allowed the scope of allowable injuries to be determined. Considering each of these inputs, a panel of experts convened to first define the absolute highest level of injury that could occur and still achieve a successful mission. Once this level was defined, the panel began buying-down the risk with other considerations: ethical, medical, political, and programmatic.

As a first step to evaluating the risk tolerance for dynamic phases of flight, an acceptable injury risk and injury scale, similar to the Abbreviated Injury Scale (AIS) used in automotive medicine but relevant to the spaceflight environment, was needed. Because crewmembers may need to perform certain critical functions (such as opening a hatch), an injury scale was needed that not only considered severity but also functional impacts of the injury. In addition, NASA is concerned with the long-term effects of an injury. If an injury is not severe and doesn't hinder egress but renders a crewmember disqualified for future flight opportunities, such an injury would be considered severe in the NASA environment.

The next input into the process was to gather injury statistics from current and previous spaceflight programs and other analogous environments. The data were to give context to the panel members. This context was thought important, as it is difficult to perceive what a particular injury risk rate really means in a real-world context.

Finally, the injury probabilities associated with dynamic events were investigated. This process was originally applied to the Orion program, but can be used for other programs as well. The probability of occurrence is important, as designing for a nearly impossible scenario may influence the safety of a nominal scenario, thus reducing the overall risk to the crew. Once each scenario was determined, the associated crew tasks were also investigated. Because crew tasks for one scenario may be more involved than in another scenario, the more involved scenario may require a lower risk of injury to have a successful outcome.

A panel of experts, with expertise in injury biomechanics related to human spaceflight, military aviation, general aviation, automotive, automotive racing, and medical fields, was assembled. The three main inputs developed here were given to this panel for review. Based on these inputs and their collective

experiences, the panel arrived at a set of recommendations for defining acceptable risk guidelines for future capsule-based spaceflight missions.

OPERATIONALLY RELEVANT INJURY SCALE

Many injury scales have been developed for evaluating human-injury severity and outcomes in other fields. The most widely used of these scales is the AIS developed by the Association for the Advancement of Automotive Medicine [1, 2]. According to the AIS handbook, the AIS is "an anatomically-based, consensus-derived, global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale". The AIS reflects severity with regard to survivability but not significance within an operational context. For NASA, a scale is needed that not only categorizes injury by severity but also accounts for an astronaut's ability to operate and carry out the mission in a spaceflight environment.

For the majority of automotive accidents, an injured person is required to do very little following the incident. Medical personnel can often be on the scene and provide care within a matter of minutes. In spaceflight, returning capsules can land in distant locations where the availability of medical assistance can be hours away. What may be categorized as a minor injury could have greater ramifications in the spaceflight environment if, say, it prevents a timely egress from a space capsule that is taking on water. In addition, a relatively minor injury could cause permanent disability. Even if the disability is minor and has little impact on daily life, such a disability could disqualify a crewmember from flight status, thus representing a significant loss to the agency. Such an ORIS could also be of use to the military where injured soldiers may still be required to hold an enemy at bay or execute other important functions post-crash to survive the incident.

The ORIS consists of three main components. The first component, injury severity (IS), is adopted directly from the AIS system scale. Table 1 shows the severity codes as defined by the AIS handbook. The AIS-severity code is taken from the AIS post-dot code, which is the single digit to the right of the dot in the AIS coding system. For the ORIS, an IS score of 0 was added to the standard AIS to indicate no injury.

Table 1. Operationally Relevant Injury Scale Inputs

Score	AIS Description	Self-Egress Capability	Return to Flight Status
0	None*	No Impact	No Delay in Return
1	Minor	Able with minor impact (within required time)	Short Delay in Return (< 3 mo)
2	Moderate	Able with Major impact (not within required time)	Intermediate Delay in Return (<1 yr)
3	Serious	Unable without assistance	Long Delay in Return (>1 yr)
4	Severe	Unable, requires rescue and/or stabilization	Ended Flight Status/DQ'd
5	Critical		
6	Maximal		

*Not included in the AIS definition

The AIS dimensions of severity include: threat to life, mortality, length of hospitalization, cost, amount of energy dissipated, temporary or permanent impairment, quality of life, and other factors. AIS severity is well correlated with mortality/survival, but mortality is not a sole determinant of AIS severity. Although all the dimensions of AIS severity are used to validate the AIS coding system, the ORIS takes the simplified view of AIS as simply the threat to life (survivability) and treatability of the injury.

The ability to self-egress (SE) is the second component that addresses the performance of critical crew tasks immediately following landing. An ordinal scale was developed to differentiate the levels of egress capability. The time a crewmember takes to egress in an emergency scenario is used to delineate between classifications (Table 1).

The final component of the ORIS is the consideration of how the injury could affect the return to flight status (RFS) of the crewmember. Although some of the severity dimensions from the AIS, such as length of hospitalization and quality of life, do reflect the long-term outcomes of an injury, RFS is specific to human spaceflight readiness, qualification and capability, and differs from the AIS severity dimensions. The RFS is a subjective measure when assessed on an ordinal scale because each person is different and evaluation of outcomes is inherently difficult to normalize across individuals. Nevertheless, there is considerable experience within the Johnson Space Center's Space Medicine group, which includes flight surgeons and medical operations personnel, to allow experienced judgment of RFS predictions. Table 1 shows the scale developed to assess the RFS component.

It should be noted that this classification is intended to indicate the RFS health, not necessarily that a crewmember will actually return to flight or be assigned a crew position in this timeframe. For all members of the Astronaut Corps, there are functions of flight status beyond spaceflight that include T-38 flight status and other activities. However, the RFS in question is regarded as the ability and

performance readiness level for spaceflight duty. The RFS does not include time needed for rehabilitation that is normally associated with returning crewmembers.

The three factors used to determine the ORIS classification – IS, SE, and RFS – were combined using Equation 1 to derive a total score and final classification. The weighting of each factor was reached by consensus with NASA flight surgeons and reflected the relative risk between each factor. For example, if a crewmember was unable to egress the vehicle, then severity and flight status did not matter as the crewmember may not be able to survive. Thus, the SE factor was rated higher than the other two factors.

Equation 1. ORIS Score Calculation

$$Score = \sqrt{0.25 \cdot (IS)^2 + 0.5 \cdot (SE)^2 + 0.25 \cdot (RFS)^2}$$

The final classification is determined by rounding the resulting score up. Thus, a score of 0 is not an injury, a score greater than 0 and less than or equal to 1 is a Class I injury, a score greater than 1 and less than or equal to 2 is a Class II injury, a score greater than 2 and less than or equal to 3 is a Class III injury, and a score greater than 3 is a Class IV injury.

A number of key assumptions were used in the scoring process. The first assumption simply means that all of the weighting factors in the formula must sum to 1.0. This simplified the development of the formula. All the numbers produced by the formula were rounded up to make the scale more, rather than less, conservative. A key assumption was to assume that any value of IS greater than or equal to 4 would yield at least a Class IV in the final ORIS classification. This decision was made after a review of the AIS coding manual, which showed that the AIS system deals with injuries that are much more critical and life-threatening than for NASA's purposes. In other words, no injuries of AIS 4+ were found that would not result in at least a Class IV in our classification system. Similarly, any IS score of a 3 would be at least a Class III injury and any injury with a score greater than 3 would result in a Class IV injury classification. Finally, it is assumed that in nominal situations recovery would occur within 2 hours. Progression of injuries was not included in the scale. Estimating progression on a global scale was not feasible and detracts from the main purpose of the scale, which was to aid designs to prevent injuries.

It is recognized that not every combination of factors was reasonable or even plausible. For example, it would not be reasonable to have an IS of 6 with no impact to egress (SE=0) or no delay in RFS (RFS=0).

Injuries such as inhalations, burns, etc., which are not caused by landing impact but may pose a risk during the overall landing phase, were excluded from the injury classification system. This scale was not intended to serve as an operational tool for treatment but rather as a vehicle and mission design analysis tool. Vehicle and system analysts can test or simulate with differentiation between levels of predicted injury to improve injury mitigation. The implementation of this injury scale is dependent on the availability of validated analysis models and techniques that accurately reflect biomechanical injury causation and prediction.

For the purposes of this exercise, the panel decided to use a generalized statement of the injury classifications. These approximate definitions were chosen to simplify the discussions of acceptable risk:

- Class I: Minor injury that would not impede performance or egress, no long-term health risks
- Class II: Moderate injury that may delay self-egress, possible short-term health risks
- Class III: Significant injury that would require assisted egress and subsequent survival operations; possible long-term health risks
- Class IV: Severe injury and possible threat to life, probable long-term health impacts

ANALOGOUS ENVIRONMENTS AND HISTORICAL SPACEFLIGHT PROGRAMS

Statistics from analogous operational environments were examined to help develop a summary table. The table includes a calculation for number of injuries per crash (or off-nominal landing) as well as the number of injuries per sortie. This information helps define the relative risk of injury (by ORIS class) every time an occupant enters a vehicle. The definition of sortie and crash depends somewhat on the environment being considered and the type and quality of the data set provided to NASA. The definitions used in developing the summary table are described in the following section for each type of environment that was examined.

PREVIOUS SPACEFLIGHT PROGRAMS

Historic spaceflight data give the best comparison for future crewed-vehicle designs; however, due to the limited number of flights and differences in vehicle designs, it may not give a complete picture. The team investigated all of the U.S. human spaceflight vehicles as well as the Russian Soyuz to glean a better understanding of risk associated with each.

During the Mercury program, there were six manned flights (two suborbital and four orbital). The Gemini program consisted of 10 manned flights with two crewmembers each. For Apollo, a total of 11 missions were flown with three crewmembers each, for an overall total of 59 human exposures. During the Mercury, Gemini, and Apollo programs, only one landing-related injury occurred and it was caused by a camera striking a crewmember in the head and knocking him unconscious [3]. Although this moderate injury was not associated with inertial responses, interaction with the seat and/or suit, it was included in the analysis for completeness. The landing was considered to be the hardest of the Apollo era. The Apollo 15 mission suffered a chute-out condition, resulting in an additional three crewmembers being exposed to off-nominal landings for a total of six off-nominal exposures. No other injuries were reported in the Mercury, Gemini, and Apollo landings.

Space Shuttle Program statistics were also examined and included in the summary table. However, NASA and most of the commercial developers are currently designing capsule-based space vehicles with landing dynamics that are quite different from the Space Shuttle. Space Shuttles landed on a runway with very little acceleration felt through the vehicle into the crewmember's seat. In a nominal landing there would be no expectation of injury at such low thresholds.

For Shuttle off-nominal conditions, there were two Orbiter accidents that included components related to the risk of injury due to dynamic loads. The Space Shuttle *Challenger* accident occurred during powered ascent. As no launch abort system was available, the crew compartment separated from the vehicle wreckage and remained intact until hitting the ocean surface at 207 mph imparting approximately 200 G on the crew [4]. The Space Shuttle *Columbia* broke up during reentry into Earth's atmosphere. During the accident, the crew was exposed to a dynamic-rotating environment identified as a potentially lethal event by the investigation team [5]. Other than these two cases, there were a few select cases of injury during nominal landings. With the assistance of NASA flight surgeons, a review of related-Shuttle injuries was performed. For the summary table, a crash was defined as an exposure of the crew to higher-than-expected dynamic load (i.e., the *Columbia* and *Challenger* accidents). Sorties are defined simply by the total number injuries that occurred per Shuttle-crew flights, including the two failed missions.

For studying the impact of a capsule-style spacecraft, the Soyuz represents a closely related analog to Orion. No other space program has more missions and thus more landings than the Soyuz. An understanding of the Soyuz system is vital to developing the next-generation capsule-style spacecraft, whether planned for land or water landings. In comparing the Soyuz with Orion, some design differences include the specific shape and style of the vehicle, number of parachutes, seating system, posture of the crew, suit design, and land versus water landings. Key similarities are obvious: a capsule-style spacecraft returning from orbit with parachutes for final touchdown, a seated-restraint system contained within a small capsule, presence and placement of recovery forces, and use of pressure suits, to name just a few.

The Soyuz program has experienced a small number of fatalities due to failure of vehicle systems. One such case was the result of decompression of the vehicle during reentry. This vehicle did experience a nominal automatic landing, so it was not included in the calculation of injury risk. However, there is one known case of parachute failure that can rightly be attributed to a forceful and fatal impact. In addition, Soyuz landings have resulted in a number of injuries, particularly during hard landings. The number of hard landings is not fully known as acceleration data have not been obtained. However, hard land landings are a key factor in Soyuz landing risk, thereby raising the level of observed minor injuries. For analysis purposes, injury occurrence was defined to the extent possible from available sources. Detailed injury reports or statistics were not formally obtained from the Soyuz program; instead, an extensive literature search was conducted [6-8]. A crash was defined as a hard landing. Sortie cases were calculated using the total number of Soyuz missions regardless of the changes in vehicle design and upgrades that occurred throughout the decades of history in the program.

Military Environments

For analogous environments, fixed and rotary wing aircraft data were examined from the U.S. Armed Forces. Data from the U.S. Air Force (USAF), U.S. Army, and U.S. Navy were provided to NASA. Unfortunately, specific injury rates were not included in all instances. Instead, in some cases, the data were categorized by mishaps, which did not distinguish human injuries from property damage. Mishap severities are categorized by Class A-D, where Class A is a fatality or greater than $2 million in property damage, Class B incidents result in either permanent disability (3 or more personnel requiring

hospitalization) or the total cost of property damage is greater than $500,000. Class C incidents result in injury that causes lost time at work and greater than $50,000 in property damage. Class D mishaps cause either injury resulting in medical treatment or $2,000 or more in property damage [9].

The U.S. Army Aeromedical Research Laboratory provided mishap data in a variety of forms. The primary dataset included rotary and fixed wing mishap statistics for years 2003–2008, detailing the total number of flight hours and Class A-D mishap rates [10]. Other data included statistics by aircraft type. It was assumed that each A-D classified mishap resulted in a corresponding injury, although this will result in an overestimation of the injury rates. These data are included in Table 2 and are shaded to denote that these data are mishap rates and not true injury rates. During continued collaboration with the U.S. Army, an attempt was made to access (through the Army Combat Readiness/Safety Center) more detailed information on injuries that would more accurately reflect injury rates and statistics per crash and flight hours. This effort has been unsuccessful to date; therefore, the reviewed statistics are based on the previously stated assumptions. For this dataset a crash is defined by a mishap, whereas a sortie is defined by the total flight hours/average sortie length (assumed 8-hour average).

Table 2. Comparison of Injury Risk Exposure and Crash Injury Statistics for Analogous Operational Environments

	Injuries per Sortie					Injuries per Crash				
	I	II	III	IV	Total	I	II	III	IV	Total
Mercury, Gemini, and Apollo	0%	1.7%	0%	0%	1.7%	0%	17%	0%	0%	17%
Shuttle	0.73%	0.0%	0.0%	1.7%	2.4%	0%	0%	0%	100%	100%
Soyuz	4.6%	0.36%	0.0%	0.71%	5.7%	21%	3.4%	0%	6.9%	31%
US Army Fixed Wing	0.040%	0.030%	0.012%	0.0021%	0.084%	48%	35%	14%	2.5%	100%
US Navy Fixed Wing	0.094%		0.017%	0.02%	0.13%	68%		12%	57%	92%
USAF Fixed Wing	0.020%			0.007%	0.027%	32%			12%	44%
US Marines Fixed Wing	0.12%		0.024%	0.02%	0.17%	62%		13%	52%	88%
US Army Rotary Wing	0.0027%	0.0029%	0.00066%	0.0012%	0.0075%	36%	40%	8.8%	16%	100%
US Navy Rotary Wing	0.054%		0.015%	0.022%	0.091%	59%		17%	104%	101%
USAF Rotary Wing	0.019%			0.0081%	0.027%	37%			15%	52%
US Marines Rotary Wing	0.055%		0.011%	0.068%	0.13%	59%		12%	260%	145%
NASCAR	0.021%	0.033%	0.022%	0.0024%	0.078%	0.36%	0.58%	0.39%	0.043%	0.36%
IRL	0.048%	0.070%	0.075%	0.011%	0.20%	1.6%	2.3%	2.5%	0.35%	6.7%
Passenger Vehicles	0.00081%			1.3e-4%	8.3e-4%	44%			0.67%	44%

Mishaps, not direct injury rates

U.S. Navy fixed and rotary-wing data were provided to NASA by the Navy Aerospace Medical Research Laboratory for mishaps occurring in fiscal years 1980–2009 [11]. Unfortunately, specific injury rates are not provided with this data set either. As with the Army data set, these data are categorized primarily by mishaps that do not delineate injuries from property damage. Mishap severities are categorized by Class A-C for flight/ground and fixed/rotary-wing crashes (and for multiple aircraft types). In addition, general fatality rates and statistics were provided that allowed a detailed analysis of Class IV injury rates. In the remaining mishap data, it was necessary to assume that each mishap classified B & C resulted in a corresponding injury, the Class A mishap rate was used to determine the total number of crashes. For

this dataset a crash is defined by a mishap, whereas a sortie is defined by the total flight hours/average sortie length (assumed 8-hour average) as shown in Table 2.

The Air Force Safety Center publishes mishap data for aircraft by fiscal year [12]. These data include the following categories of information by year: number of Class A mishaps, rate of Class A mishaps (per 100,000 flight hours), number of Class B mishaps, rate of Class B mishaps (per 100,000 flight hours), number of destroyed aircraft, rate of destroyed aircraft (per 100,000 flight hours), number of pilot fatalities, number of all fatalities, and number of flight hours. After compiling the lifetime statistics for each aircraft type, the number of pilot fatalities was used to determine the Class IV (fatal) injury risk. Using the number of total mishaps and the number of pilots for each aircraft type, the total risk of fatal injuries was determined based on the pilot fatalities. The rate of injures were determined based on the number of Class B mishaps compared to the total number of mishaps. This methodology was applied to both fixed and rotary wing datasets; all Class B mishaps are not injurious and will overestimate the total injury risk, but are consistent with the method used for other military service branches. Although all fatalities (including those not caused by inertial loads) are included, this methodology will also overestimate injury risk. A crash is defined by a mishap, whereas a sortie is defined by the total flight hours/average sortie length (assumed 8-hour average). The results are included in Table 2.

U.S. Marine data were provided to NASA by the Navy Aerospace Medical Research Laboratory in addition to the Navy mishap data [11]. As with the Navy dataset, specific injury rates are not provided but instead are categorized primarily by mishaps, which do not delineate injuries from property damage. Mishap severities are categorized by Class A-C for flight/ground and fixed/rotary wing crashes (and for multiple aircraft types). General fatality rates and statistics are provided, which allow a detailed analysis of Class IV injury rates. In the remaining mishap data, it was necessary to assume that each mishap classified B & C resulted in a corresponding injury, the Class A mishap rate was used to determine the total number of crashes. For this dataset a crash is defined by a mishap, whereas a sortie is defined by the total flight hours/average sortie length (assumed 8-hour average) as shown in Table 2.

AUTOMOTIVE

A comprehensive set of crash and injury data was obtained from the National Association for Stock Car Auto Racing (NASCAR) for the years 2003–2008 through a Space Act Agreement. The primary benefit of the NASCAR dataset was the possession of both crash dynamics data – obtained through onboard crash data recorders – and the resulting injuries immediately following the event. NASCAR personnel provided narrative descriptions of the crash and impact events, and reviewed each injury-related event to exclude cases where vehicle intrusion was the principal cause of injury.

A review of the injury exposure risk and crash/injury ratio for the NASCAR environment was conducted. A total of 41 injuries were identified amongst 4015 impact events. Surprisingly, the risk of serious injury from racing impacts is actually much lower than what is popularly assumed. Although many of the 4015 events are considered low impact, the advances in NASCAR's occupant protection designs has increased the impact threshold at which any type of injury occurs [13].

Combining the NASCAR data with the other analogous operational environments required a few assumptions. First, an injury was defined by a reported occurrence from the NASCAR dataset, including the AIS code descriptor and a narrative description of the injury. It is reasonable to assume some lesser injuries (contusions, etc.) may have been unreported during this timeframe. Further, a crash was defined by any impact event that triggered the crash data recorder, which was set to a 4-G threshold. It is understood that not all of the impact events represent a "crash" by the classical definition, but are nevertheless a significant load within our criteria. To calculate the exposure risk, it was necessary to develop a definition for a "sortie" in the NASCAR context and to make an assumption for the number of sorties in the timeframe. After consultation with experts from NASCAR, a sortie was defined as "any time the driver enters the car during an event". With this definition, a general assumption was made that each driver may log four to five sorties per race event including training, test, and qualification runs as well as the race event itself.

A similar evaluation as that performed for NASCAR was conducted with data provided by IndyCar. With the cooperation of IndyCar and in accordance with an approved Space Act Agreement, a listing of crash and injury statistics was provided for years 2003–2008. In this dataset, a total of 38 injuries were observed out of a total of 570 crashes. In addition to the statistical data provided, crash recorder data were provided for the years 2006–2008 in a standardized format. Data before 2006 may be available but in various nonstandardized formats.

Although there are many clear differences in the vehicle design and race configurations with IndyCar and other racing contexts, many key similarities hold for comparison purposes. From a crash and injury dynamics standpoint, the specific orientation of the driver or even the type of vehicle is not paramount for determining injury exposure risk in this analogous environment. As with the NASCAR dataset, an injury for IndyCar was defined, according to the track doctors, with a record in their database as an observed injury. The on-board event data recorders capture 1 minute of data before and 30 seconds of data after a crash. A sortie was defined as any time the driver enters the car for an event. Again, a working assumption for the number of sorties was made following consultation with the IndyCar representative to the project and was set at three sorties per car per race event, which includes practice laps, qualification, and the race event itself.

Passenger vehicle fatality and injury information was obtained from the National Highway Traffic Safety Administration. Summary data on number of vehicle miles per year, number of fatalities, number of injuries, and number of accidents were provided for the period of 2000–2010 [14]. The dataset contained 402,000 fatalities, 26.2 million injuries, 60 million accidents, and 32.2 trillion vehicle miles traveled. In addition, the average length of a single trip was estimated from published data from the Bureau of Transportation Statistics [15] showing the average trip is 10.0 miles. The results from these data are shown in Table 2. Similar to rotary-wing aircraft, the number of occupants in a single accident may be higher than 1, so these numbers may overestimate the risk.

COMPARISON

The results of crash and injury statistics across these analogous operational environments are summarized in Table 2. This table shows the calculated injuries per crash (or off-nominal landing) as well as the injuries per sortie. The purpose of the table is to show the relative risk of injury (by ORIS class I [most severe] through IV) every time an occupant enters a vehicle. This exposure risk is independent of whether the vehicle experiences a contingency event (crash, off-nominal, or other unexpected event). In addition, the table shows the change in injury risk once that particular occupant is in a contingency scenario. In other words now that an impact is imminent it answers the question: What is the risk of injury?

LANDING PROBABILITIES AND ASSOCIATED CREW TASKS

Given the risk context from analogous programs, the next step is to understand what scenarios are probable, likely, or remote, and then determine what the crew is expected to do in those situations. The purpose of this step is to balance the total risk of the system so that one scenario doesn't carry the majority of the risk, or so that a remote scenario doesn't drive design decisions that could ultimately reduce the total safety of the vehicle.

A list of all possible abort and landing scenarios was gathered for the Orion vehicle using the logic diagram shown in Figure 1. A pattern of 28 unique landing scenarios emerged based on the following driving factors: whether immediate egress is required, whether suit-doffing is required, which hatch should be used for egress, and whether external recovery forces were necessary (Table 3). Although there are 59 possible combinations, mission rules limit the number of plausible combinations to the 28 shown.

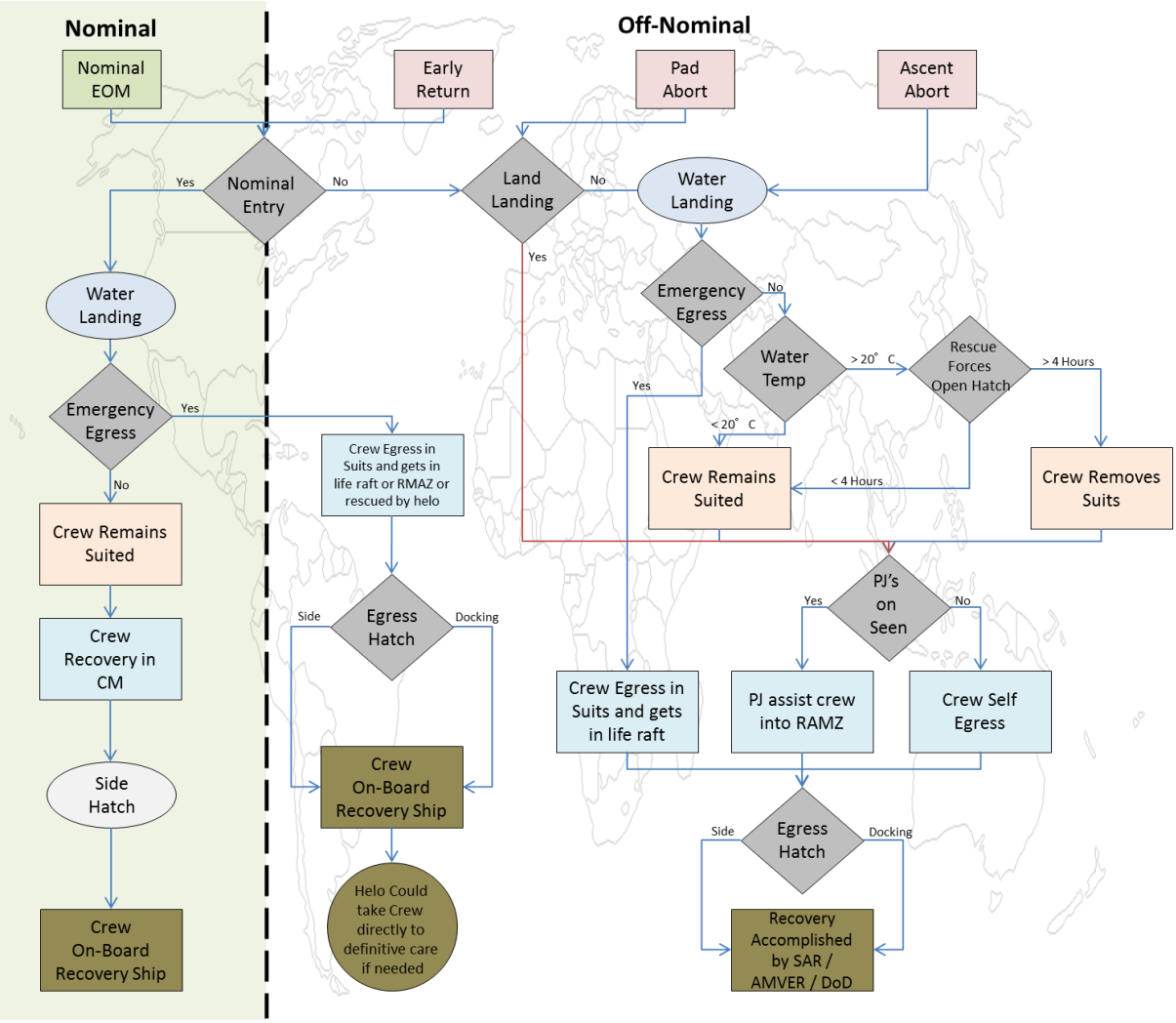

Figure 1. Landing condition logic diagram.

Table 3. List of Possible Abort and Landing Scenarios

Scenario	Condition	Entry	Landing	Emergency Egress	Doff Suit	Rescue Forces	Hatch	Comments
1	Nominal EOM	Nominal	Water	No	No	Yes	Side	Nominal case
2	Nominal EOM	Nominal	Water	Yes	No	Yes	Side	Near landing forces
3	Nominal EOM	Off-Nominal	Water	No	No	No	Side	Off-nominal reentry will be within 4 hours of rescue
4	Nominal EOM	Off-Nominal	Water	Yes	No	No	Side	
5	Early Return	Nominal	Water	No	No	Yes	Side	Early return would be to water, but unknown conditions. Could be >4 hours until recovery and water temps could be greater than 20°C.
6	Early Return	Nominal	Water	Yes	No	Yes	Side	
7	Early Return	Nominal	Water	No	No	No	Side	
8	Early Return	Nominal	Water	Yes	No	No	Side	
9	Early Return	Nominal	Water	No	Yes	Yes	Side	
10	Early Return	Nominal	Water	Yes	Yes	Yes	Side	
11	Early Return	Nominal	Water	No	Yes	No	Side	
12	Early Return	Nominal	Water	Yes	Yes	No	Side	
13	Early Return	Off-Nominal	Water	No	No	Yes	Docking	
14	Early Return	Off-Nominal	Water	Yes	No	Yes	Docking	
15	Early Return	Off-Nominal	Water	No	No	No	Docking	
16	Early Return	Off-Nominal	Water	Yes	No	No	Docking	
17	Early Return	Off-Nominal	Water	No	Yes	Yes	Docking	
18	Early Return	Off-Nominal	Water	Yes	Yes	Yes	Docking	
19	Early Return	Off-Nominal	Water	No	Yes	No	Docking	
20	Early Return	Off-Nominal	Water	Yes	Yes	No	Docking	
21	Pad Abort	--	Water	No	No	Yes	Side	Near shore, rescue forces, no high sea states
22	Pad Abort	--	Water	Yes	No	Yes	Side	
23	Pad Abort	--	Land	No	No	Yes	Side	
24	Pad Abort	--	Land	Yes	No	Yes	Side	
25	Ascent Abort	--	Water	No	No	No	Side	North Atlantic, cold water, no rescue forces, could be high sea states
26	Ascent Abort	--	Water	Yes	No	No	Docking	
27	Ascent Abort	--	Water	No	No	No	Side	
28	Ascent Abort	--	Water	Yes	No	No	Docking	

These scenarios were assigned probabilities based on a preliminary probability risk assessment (PRA) conducted for the Orion program. Based on the PRA, cases with extremely low probabilities were excluded (less than 10^{-6} probability of occurrence) and cases with similar operational conditions were combined (e.g., ascent abort and pad abort). This pared the list to three driving cases: a nominal landing with no emergency egress, a pad or ascent abort, and a nominal landing requiring immediate egress. These scenarios are independent of parachute failures or other hard landing conditions. It should be noted that the numbers do not necessarily reflect the current design and were only considered as a relative comparison for the purposes of the acceptable risk process.

The type of tasks the crew would need to perform immediately post-landing was identified for these three landing situations. Any injury sustained as a result of landing impact or abort cannot impede the crew's ability to execute these tasks without putting the crew and mission at risk. The results of this exercise are shown in Table 4. Other operational considerations include motion sickness, sea state interference, and spaceflight deconditioning. The driving operational factors in formulating injury risk guidelines include: the need for immediate/emergency egress, the need to doff the suit, the path of egress (side or docking hatch), and whether (and when) external recovery forces are available to assist.

These driving operational factors are not unique to Orion but can be extended to future commercial vehicles as well.

Table 4. Examples of Key Landing Scenarios, Probabilities and Associated Crew Tasks (not all shown)

Case	Return	Entry	Emergency Egress	Suit doff before egress	Hatch	External/PJ assistance within 2h	Overall Probability	Crew Tasks
1	Water	Nominal	No	No	side	No – Crew recovery in CM	99.58%	• Monitor shut down task • Remove helmet and gloves if desired • Raise visors within 15 minutes of landing • Select post landing communication • Reach water and emesis bags
2	Water	Pad or Ascent Abort	No	No	side	Yes	0.20%	• Shut down CM • Remove umbilical and restraints • Retrieve emergency equipment • Open side hatch • Deploy emergency equipment • Climb over hatch seal and fall into water • Float till recovery forces arrive
3	Water	Nominal	Yes	No	side	Yes	0.00021%	• Shut down CM • Remove umbilical and restraints • Open side hatch • Climb over hatch seal and fall into water • Float till recovery forces arrive

The general nature of all of the tasks is similar in the three scenarios and any injury would have similar impacts on each. The panel reasoned that the scenarios presented are preliminary and could change as the design matured. So instead, based on their recommendations on generic "nominal" and "off-nominal" scenarios, the final recommendation could be extended to other scenarios as they arise. This also allows the panel recommendations to be applied to future vehicles as well, as long as future vehicles require similar crew tasks.

PANEL RECOMMENDATIONS

DETERMINING THE HIGHEST ACCEPTABLE RISK

Based on the ORIS, historical and analogous environment risk information, landing probabilities, and associated crew tasks, the next step was to determine the highest possible acceptable risk. Before this could be accomplished, several ground rules and assumptions were required:

- Analysis assumed each crewmember will perform independently during egress tasks (conservative approach), which focused on the "weakest link"/most injured crewmember
- Assumed crew could successfully complete all post-flight tasks if uninjured
- Off-nominal land landing (pad abort) would have advanced trauma life support (ATLS) medical care to the crew in 30 minutes or less
- Off-nominal water landings would not have ATLS medical care to the crew in 30 minutes or less

For NASA, the maximum possible acceptable risk was determined based on mission success but could have easily been based on other factors. The goal was to get consensus on a level that is a "line in the sand," which no one would argue for any higher level of acceptable risk. Using the criteria of mission success, the team first considered the risk of Class III (severe) and IV (fatal) injuries. The panel agreed that to have a successful mission outcome no incidence of Class III and IV injuries should occur within 95% confidence (based on a binomial distribution). In addition, minor injuries (Class I) by definition would have no impact on mission success, so there could be 100% incidence.

A custom MATLAB program was written to further illustrate the "real" risk of injury for a give scenario [16]. The program took either the percentage risk of injury or the expected number of injuries and determined the corresponding matched number. These calculations were made using a binomial distribution based on a total of 80 flights with 4 crewmembers per flight (320 total exposures). More information on this method can be found in Appendix A.

The panel then considered nominal and off-nominal landing conditions. In particular, the panel discussed the possibility of allowing Class III (severe) injuries for pad abort conditions. This was deemed to be allowable if search and rescue (SAR) forces could reach the crew in less than 30 minutes. Although this requirement was only possible for pad abort cases (and the probability of such aborts are low), the team members revised their highest acceptable risk to include up to two of these types of injuries on a given mission during a pad abort. This represented the highest risk the panel would accept based solely on mission success criteria.

The panel then worked through additional considerations that would preclude such a high level of injury risk. As the panel already determined that no Class III or IV injuries are permissible (except in the case of a pad abort), the discussion mainly centered on the acceptable levels of Class I and Class II injuries. The following considerations were used to formulate the final recommendation.

Obviously, injuring crewmembers for every flight would not be ethical, particularly if there are methods for mitigating such risk. In addition to the ethical considerations, there are medical considerations. Allowing crewmembers to be injured often could complicate future medical outcomes or create pre-existing conditions, and long-term effects could also be possible. The panel also discussed additional political considerations. Because injuries, incurred in a nominal landing, could harm NASA's public image, mitigating injuries to a reasonable level is also needed. From a NASA programmatic stance, a high rate of injury could incur significant post-landing care, which is undesirable. In addition, because the probability of landing is always 1, a low risk of injury is needed to lower the overall risk of injury, as compared to the other analogous environments.

A subset of driving cases was considered for establishing an acceptable risk level, including ascent abort water landing, end of mission (EOM) water landing (with any combination of a major system failure), and a land landing (Table 5). The panel recommended injury probabilities in the table to represent the maximum allowable occurrence for any individual crewmember and are based on 80 flights with four crewmembers per flight. A "worst-case" probabilistic view of the likelihoods for each scenario was used

to derive the table probabilities. In other words, given a contextual framework from Soyuz, Shuttle, and other programs, it could be assumed that the true off-nominal rate for landings would actually be higher than is currently predicted for Orion. In light of this historic track record, off-nominal cases were analyzed with a probability of 1% occurrence for each. The ratios of acceptability and calculations of injury probabilities are proportional to this assumption, and should be adjusted to account for actual off-nominal landing rates as needed for forward work.

Table 5. Determination Approach for Acceptable Orion Landing Injury Risk (Nominal/Off-Nominal Landing Cases)

Assumes: 80 Landings over Program Life-4 Crewmembers per Landing, 320 Total Crew Landings 95% Confidence		**Nominal**		**Off-Nominal^**					
		EOM Nominal Water Landing or Pad Abort Water Landing		**Ascent Abort Water Landing**		**EOM Water Landing with Parachute Failure, High Winds, High Sea State**		**Pad Abort Land Landing**	
P(Landing)		99.6%		<1%		<1%		<1%	
Injury Class		Expected Number of Injuries	Probability of Injury	Expected Number of Injuries	Probability of Injury	Expected Number of Injuries	Probability of Injury	Expected Number of Injuries	Probability of Injury
Minor	I	18	4%	3	56%	3	56%	4	100%
Moderate	II	3	0.42%	2	39%	2	39%	3	70%
Severe	III	0	0.1%	0	17%	0	17%	0 (2)*	10% (30%)*
Life-Threatening	IV	0	0.02%	0	6%	0	6%	0	10%
All Classes	I-IV	21	4.71%	5	100%	5	100%	9	100%

*Acceptance of this injury risk assumes SAR forces will get access to the crewmembers within 30 minutes of the mishap occurrence
^Number of expected injuries for Off-nominal was determined using 1% probability of occurrence. The current design probabilities are much lower.

RESULTS

The following recommendation for acceptable landing injury risk (Table 6) was approved by unanimous consensus of the expert panel. The panel also agreed that in the event of a change in the expected number of flights, the ratio of expected number of injuries to exposure was the critical outcome of the recommendation. This implies that the calculated probability of injury could change based on the expected number of flights.

Table 6. Recommendation for Acceptable Orion Landing Injury Risk (All Landing Cases)

Injury Description	Injury Class	Expected Number of Injuries	Probability of Injury
Minor	I	23/320	5%
Moderate	II	6/320	1%
Severe	III	0/320 [2/320]*	0.02% [0.25%]*
Life-Threatening	IV	0/320	0.02%
All Classes	I-IV	29/320 [31/320]*	6.8% [7.4%]*

*Acceptance of recommendations in brackets assumes SAR forces will get access to the crewmembers within 30 minutes of the mishap occurrence.

EXTENDING THE RECOMMENDATIONS BEYOND ORION

Although current recommendations are meant to be independent of the Orion design, several key assumptions are linked to it, namely the number of crew-flights and the occurrence of off-nominal landings. Probabilities of injury can be calculated for different numbers of crew landings while still maintaining the ratio of expected number of injuries to the total number of crew flights. Table 7 shows the probability of injuries for various numbers of total crew flights. Taking the median of the values shown for each injury class, the probability of injury for each class can then be estimated irrespective of the number of crew flights.

Table 7. Maximum Nominal Risk Levels for each Injury Class Based on Number of Crewmembers Flown Over the Course of the Program

	Number of Crew-Flights								
	40	**80**	**120**	**160**	**200**	**240**	**280**	**320**	**Median**
Class I	3.49%	4.18%	4.59%	4.87%	4.68%	4.90%	5.08%	5.23%	4.8%
Class II	0.90%	1.03%	0.68%	0.86%	0.99%	1.09%	0.94%	1.03%	1.0%
Class III	0.13%	0.45%	0.30%	0.22%	0.18%	0.34%	0.29%	0.26%	0.27%
Class IV	0.13%	0.06%	0.04%	0.03%	0.03%	0.02%	0.02%	0.02%	0.03%

To determine the off-nominal probabilities of injury, the total risk of the system would still need to meet the values in Table 7. Although each future vehicle may have different estimated probabilities of off-nominal landings, these estimates may be used as conservative estimates. Reviewing previous capsule landings for off-nominal conditions, a high number of landings were found to be off-nominal. For Soyuz, the occurrence of off-nominal landings is approximately 25%, and has been consistent even with the recent capsule design updates. For all U.S. capsule-based manned landings, the overall occurrence of off-nominal landings has been similar at 26% (Mercury had a 33% occurrence, Gemini had a 40% occurrence, and Apollo had a 9% occurrence) [17-19]. Based on this information, it was assumed that future vehicles would have a 25% occurrence or less. If the occurrence is less than 25%, then the numbers in Table 8 are conservative. A 25% occurrence of off-nominal landings should not be used as

the design requirement, as experience has shown that the true probability is often higher than the designed probability.

Table 8. Maximum Off-Nominal Risk Levels For Each Injury Class Based on Number of Crewmembers Flown Over the Course of the Program. Numbers are based on up to a 25% occurrence of off-nominal landings.

	Number of Crew-Flights								
	40	**80**	**120**	**160**	**200**	**240**	**280**	**320**	**Median**
Class I	14.0%	16.7%	18.4%	19.5%	18.7%	19.6%	20.3%	20.9%	19.1%
Class II	3.58%	4.12%	2.74%	3.43%	3.96%	4.38%	3.75%	4.12%	3.9%
Class III	0.51%	1.78%	1.18%	0.89%	0.71%	1.36%	1.17%	1.02%	1.1%
Class IV	0.51%	0.26%	0.17%	0.13%	0.10%	0.08%	0.07%	0.06%	0.11%

Table 9 shows the recommended risks for all future NASA vehicles during dynamic phases of flight.

Table 9. Recommendation for Acceptable Landing Injury Risk

Injury Description	Injury Class	Nominal Probability of Injury	Off-Nominal Probability of Injury
Minor	I	4.8%	19.1%
Moderate	II	1.0%	3.9%
Severe	III	0.03% (0.27%)*	0.11% (1.1 %)*
Life-Threatening	IV	0.03%	0.11%

*Acceptance of recommendations in brackets assumes SAR forces will get access to the crewmembers within 30 minutes of the mishap occurrence.

The assumptions used to formulate the recommendations detailed in Table 9 are:

- Expected number of injuries is based on 95% confidence of observing no more than stated number of injuries
- Off-nominal recommendations based on up to a 25% incidence of off-nominal landings
- Analysis assumes each crewmember will perform independently during egress tasks (conservative approach), which focuses on the “weakest link” crewmember most injured
- Deconditioning factors will be applied for cases where biodynamic responses and injury likelihoods would be affected by spaceflight
- Ground-based response and access to the crew varies by scenario. These assumptions need to be validated with the help of ground crews and recovery personnel
- Off-nominal land landing will have ATLS medical care to the crew in 30 minutes or less (pad abort)
- Off-nominal water landings will not have ATLS medical care to the crew in 30 minutes or less

- Application of more conservative (i.e., worst) number of injuries or probabilities of injuries should be bounding
- Discussions considered projected probabilities of landing cases, but determinations were made relative to "worst-case" likelihoods rather than current analysis
- Recommendations are process-based and are therefore expected to be independent of vehicle design and program mission rates
- Injury categories will be based on consensus of Space Medicine and flight surgeon communities, to be expressed in terms of biodynamic parameters

CONCLUSION

Table 9 embodies the position that crewmember injury risk, as represented by the existing requirements (i.e., Brinkley), can better be evaluated with an assessment that includes a classification of injuries from minor to life-threatening derived from the ORIS. By classifying injuries in this manner, program requirements can be updated to express a more modern and granular approach to risk analysis and vehicle design. Class III (Severe) and Class IV (Life-threatening) injuries should be kept to 0 acceptable injuries in these categories given the operational context, design, programmatic assumptions, and knowledge of occupant protection principles and capabilities. In contrast, the tolerance of Class I (Minor) and Class II (Moderate) injuries was increased from the current programmatic acceptable levels. In other words, a higher risk of lower severity injuries is acceptable in exchange for a lower risk of higher severity injuries. This tradeoff of acceptable injury risk is not possible within the current set of Orion's system requirements.

Table 10 shows a comparison of the recommendations identified in Table 9 with the analogous Soyuz environment. The results of the acceptable injury risk recommendation are consistent with the results of the Soyuz vehicle, which is currently deemed safe for NASA crewmembers.

Table 10. Comparison of NASA Recommendations to Soyuz Data

Injury Description	Injury Class	Nominal Probability of Injury	Off-Nominal Probability of Injury	Soyuz Nominal	Soyuz Off-Nominal
		Greater than 75% Occurrence	**Up to 25% Occurrence**	**75% Occurrence**	**25% Occurrence**
Minor	I	4.8%	19.1%	4.1%	16.7%
Moderate	II	1.0%	3.9%	0.4%	1.9%
Severe	III	0.03% [0.27%]*	0.11% [1.1 %]*	0%	0%
Life-Threatening	IV	0.03%	0.11%	0.4%	1.9%

*Acceptance of recommendations in brackets assumes SAR forces will get access to the crewmembers within 30 minutes of the mishap occurrence.

Finally, using hypothetical probabilities of nominal and off-nominal landings, the total risk of injury can be determined for any specific vehicle (Table 11). The example assumes a 97.7% rate of nominal landings and gives the resulting overall risk of injury any time someone lands in the vehicle. Although off-nominal injury risks seem high, they contribute little to the overall risk of injury.

Table 11. Total Risk of Injury

Injury Description	Injury Class	Nominal ‡ Landing Injury Probability	Off-Nominal ‡ Landing Injury Probability	Total Risk of Injury
Minor	I	4.7%	0.4%	5.1%
Moderate	II	1.0%	0.09%	1.1%
Severe	III	0.03% (0.26%)*	0.002% (0.03 %)*	0.03% (0.29%)*
Life-Threatening	IV	0.03%	0.003%	0.03%

*Acceptance of recommendations in brackets assumes SAR forces will get access to the crewmembers within 30 minutes of the mishap occurrence.

‡ Nominal landings assumed to occur 97.7% of the time, and off-nominal 2.3%

The method presented here represents a novel approach to defining acceptable risk in a way that minimizes overall risk, while at the same time developing injury risk limits that are achievable by spacecraft designers. This balanced approach will be used to develop future standards and requirements for NASA spacecraft to protect crews from dynamic loads.

ACKNOWLEDGEMENTS

This work was supported by the NASA Human Research Program through the Bioastronautics Contract (NAS9-02078). The authors greatly appreciate the assistance and advice from personnel within the NASA Engineering and Safety Center, NASA Space Medicine Division, NASA Astronaut Crew Office, U.S. Air Force Research Laboratory, U.S. Army Aerospace Medical Laboratory, and U.S. Navy Aeromedical Research Laboratory.

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APPENDIX A: BINOMIAL DISTRIBUTION METHOD

An analog of this method can be used. Consider a baseball team that has a 50-50 chance of winning a game in a 162-game season. The mean number of games they would win on average would be 81; however, the most one would expect them to win would be 91 (95% confidence level).

Similarly, if a vehicle had a 10% risk of injury on landing, the *mean* number of expected injuries would be 10 out of 100 landing exposures; however, the *most* injuries that could occur for that level of injury risk would be 15 (at 95% one-sided confidence) as shown in Figure 2.

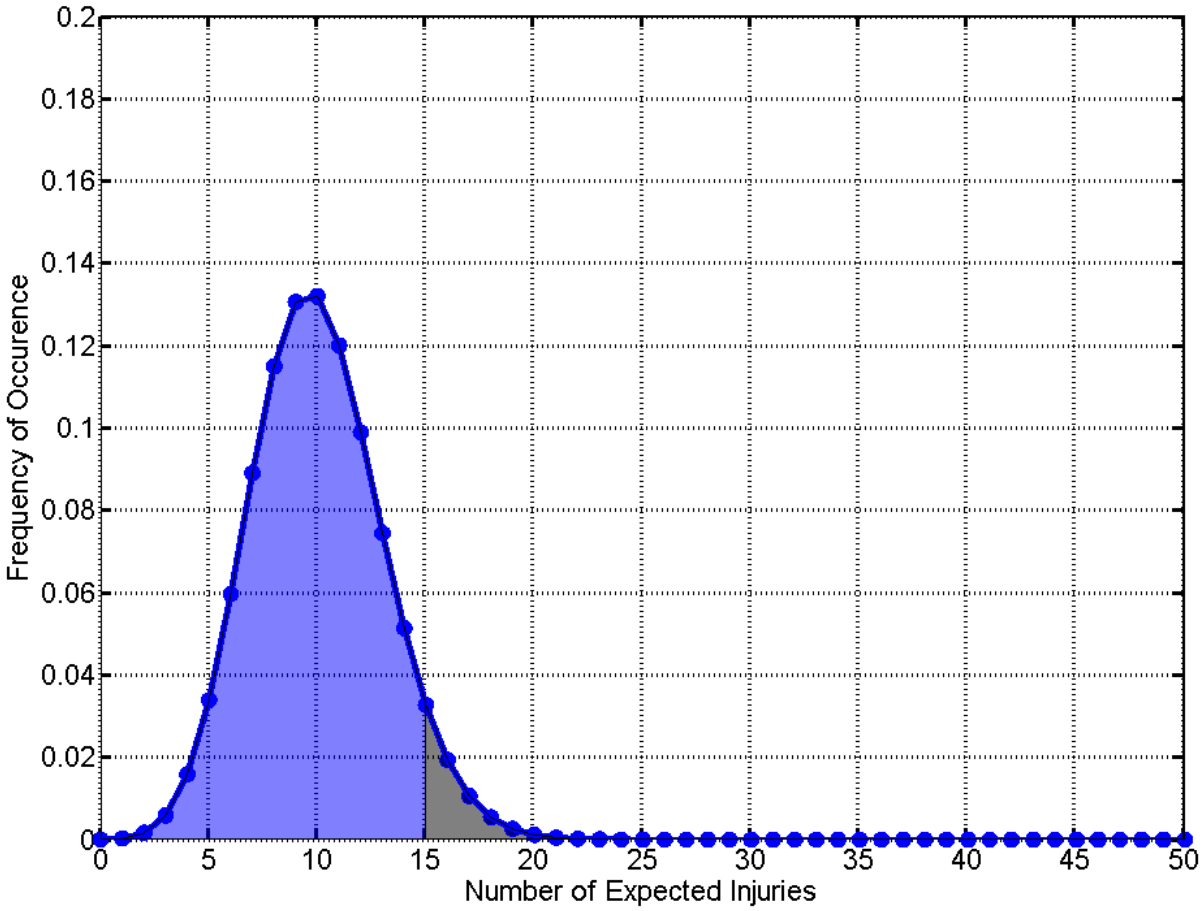

Figure 2. Distribution of probable number of expected injuries.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 2014	NASA Technical Memorandum

4. TITLE AND SUBTITLE
Defining NASA Risk Guidelines for Capsule-based Spacecraft Occupant Injuries Resulting from Launch, Abort, and Landing

5. FUNDING NUMBERS

6. AUTHOR(S)
Jeffrey T. Somers, Richard Scheuring, Bradley Granderson, Jeffrey Jones, Nathaniel Newby, Michael Gernhardt

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lyndon B. Johnson Space Center
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS
S-1147

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TM-2014-217383

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Available from the NASA Center for AeroSpace Information (CASI)
7121 Standard
Hanover, MD 21076-1320 Category: 16

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A novel approach has been developed to define acceptable risk guidelines for human spaceflight injuries occurring during dynamic phases of flight (launch, abort, and landing). These risk guidelines is a driver for both vehicle and mission design, which in turn drive cost and schedule. The approach outlined in this document was based on three inputs. First, an Operationally Relevant Injury Scale was developed to categorize injuries within the framework of the spaceflight environment. Second, a systematic consideration of injury risk in other analogous programs and historic space programs was gathered for a pragmatic examination of realistic injury probabilities. Third, estimated Orion landing types and probabilities were determined along with the type of tasks crewmembers would be expected to perform in each situation to ensure mission success. These landing scenarios helped define the range of injuries expected for capsule-based spaceflight. A panel of experts convened to define the highest level of injury allowable that still achieved mission success. Once this level was defined, the panel began buying-down the risk with other considerations. Results led to a Definition of Acceptable Risk for space-capsule landings that may be used to help set new standards to protect crews during dynamic phases of flight.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
landing; abort; launch vehicles; space capsules; injuries; risk assessment	30	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited