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Comparison of Health and Performance Risk for Accelerated Mars Mission Scenarios

Erik Antonsen MD, PhD
Baylor College of Medicine
NASA Johnson Space Center, Houston, TX

Mary Van Baalen, PhD;
NASA Johnson Space Center, Houston, TX

Integrated Medical Model Team
Binaifer Kadwa, MS
NASA Johnson Space Center, Houston, TX

Lynn Boley, RN, MS
KBR
NASA Johnson Space Center, Houston, TX

John Arellano, PhD
MEI Technologies
NASA Johnson Space Center, Houston, TX

Eric Kerstman, MD
University of Texas Medical Branch
NASA Johnson Space Center, Houston, TX

Space Radiation Analysis Group
Lori Chappell, MS
KBR
NASA Johnson Space Center, Houston, TX

Edward Semones, MS
NASA Johnson Space Center, Houston, TX

Space Radiation Element

S. Robin Elgart, PhD
University of Houston
NASA Johnson Space Center, Houston, TX

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas
77058

February 2021

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Table of Contents

Table of Figures

Table of Tables

1 Background

This document details the results for a quantitative estimate of the difference in human health and performance risk that crews would face for two hypothetical variations on Mars mission scenarios: an Accelerated Mars Mission (AMM) and a Standard Mars Mission (SMM). NASA goals for Mars mission concepts, duration, and tasks have varied over the years. While neither of the cases considered here are likely to accurately represent the initial mission to Mars, the exercise of evaluating significant differences in mission duration from an astronaut health perspective can provide bounding insight to the level of risk that is likely to be encountered in an eventual Mars mission. Medical Probabilistic Risk Assessment using the Integrated Medical Model (IMM)(1–3) and the NASA Space Radiation Cancer Risk Model (NSCR)(4,5) are used here to help mission planners gain the best insight currently available into the expected magnitude of impacts to astronaut health when undertaking a Mars mission. These impacts occur both in-mission as well as in the long-term health of the astronauts post-mission. These evaluations are currently the best available modeling estimates to characterize and bound the health risks in a proposed mission domain where humans have no experience.

An AMM would have a 4-person crew and total transit time of approximately 420 days, comprised of 6 months transit time to Mars, 30-day stay on the Mars surface with Extravehicular Activity (EVA) and rover use daily, and 7-month transit time return to Earth with Venus Fly-By.

An SMM would have a 4-person crew and total transit time of approximately 923 days, using the assumptions of Design Reference Mission (DRM) 5, transit and Mars surface stay time based on Table 4-2 from the Human Exploration of Mars DRM Addendum (6) published in 2009 and using the lowest delta V option. This is the second shortest mission option outlined in existing NASA DRM documents, the shortest being 914 days total duration. A total of 401 4-person EVAs are included for 5 EVAs every 7 days.

The mission assumptions used in this analysis are as follows:

Accelerated Mars Mission

- 180-day transit, 30-day surface, 210-day return transit
- Total Trip time **420 days**
- Crew of 4 (2 males, 2 females)
- 2 surface EVAs per day (to capture higher end of risk) per 30 days on surface for a total of 60 surface EVAs in pairs (30 per crew member)
- Solar Max radiation levels

Standard Mars Mission

- 180-day transit, 560 days surface, 183-day return transit
- Total Trip time **923 days**
- Crew of 4 (2 males, 2 females)
- 5 EVAs every 7 days during a total 560 days on the surface of Mars resulting in 401 4-person EVAs.

- Solar Max radiation levels (890 days total exposure calculation used)

Two modalities were used to provide a quantitative estimate of human health and performance risk. The Integrated Medical Model (IMM) was used to calculate in-mission medical risk, and the Space Radiation Analysis Group (SRAG) used current operational models to predict cancer risks based on radiation exposure to predict post-mission for long-term health outcomes.

2 Main Results

An AMM results in ***significantly decreased risk*** as calculated by the IMM for in-mission risk and by SRAG for long-term health risk.

The SMM carries:

- Approximately **2.9x** increased likelihood of experiencing loss of crew life (LOCL) event
- Approximately **4.7x** increased likelihood that serious medical condition would occur that would warrant medical evacuation (EVAC) if it was available
- Approximately **19%** worse Crew Health Index (CHI) that contributes to performance decrements across the duration of the mission
- Between **1.5-2x** increased likelihood of the lifetime risk of radiation exposure-induced death from cancer

The following sections and appendices describe in more detail the models used, assumptions and caveats, and provide tabular and graphical representations of the data that inform these numbers.

3 Integrated Medical Model

3.1 Background

The IMM was used to calculate the difference in medical risk between the AMM and SMM DRMs. The IMM run used for reference is S20200303-423 (7). This run was evaluated and approved for release by the Space Medicine Operations Control Board (SMOCB) at Johnson Space Center (JSC) on April 13, 2020.

Mission-level risk difference is expressed here in two primary mission-level outcomes.

1. EVAC – the likelihood of reaching evacuation criteria based on International Space Station (ISS) parameters that include: 1) potential LOCL; 2) potential significant permanent impairment; or 3) potential intractable pain.
2. LOCL – the likelihood of LOCL indicates the likelihood of losing a single crew member to an untreated or potentially untreatable medical condition during a mission.

Caveats – The IMM is an analysis tool developed for low Earth orbit (LEO) applications. It is being used here in a modified manner to provide insight to the potential comparative difference in risk for

Mars missions because it is the only quantitative tool currently available to approach this problem. The quantitative results here are a good ballpark estimate of medical events and risk, but there is insufficient capability in the tool to give a precise estimate of risk.

There are a number of assumptions that must be considered, the most important include:

1. IMM includes data and evidence based on LEO experience and terrestrial data. This limits applicability to the Mars spaceflight environment, but provides a reasonable like-for-like comparison of the effects of mission duration on medical risk.
2. A single ISS medical kit was used to model medical resources for the missions. It is expected that the mass and volume constraints on a Mars mission will result in smaller medical kits with less capability. As a result, this assessment is likely optimistic and actual risk may be greater than predicted by the IMM.
3. The IMM is baselined to ISS and does not simulate EVAs in partial-gravity environments. Specific medical conditions were 'turned off' during in-flight transit portions of the mission and 'turned on' during planetary excursion timeframes. These include major musculoskeletal and traumatic injuries that are much more likely to occur as a result of accidents or injuries on a planetary surface than in the internal spacecraft environment for transit.
4. EVAC is a parameter calculated to inform LEO risk for mission-level outcomes. Although in a Mars mission there is no possibility of evacuation, EVAC is used here to identify how often medical conditions are likely to rise to the level that would have potentially led to the evacuation of a crew member if that were possible. In the case of a Mars mission, EVAC will ultimately end in one of several outcomes: 1) complete resolution; 2) crew member disability that can potentially lead to Loss of Mission Objectives (LOMO); or 3) LOCL. For the purposes of this report, there is insufficient evidence or modeling capability to predict further than EVAC.

Additional assumptions must be recognized as limitations in any formal output from the model. Those can be found in supporting literature and are not included here for brevity (8).

4 Key Results

4.1.1 Total Medical Events

Expected total medical events are significantly lower in an AMM due to decreased amount of time for medical condition development. This includes less surface time on Mars and less total EVAs than the SMM, which significantly decreases the number of EVA-associated medical conditions. Figure 1 shows the difference in tabular and graphical format.

	TME	95% CI	
AMM	156.45	130	182
SMM	603.03	482	673

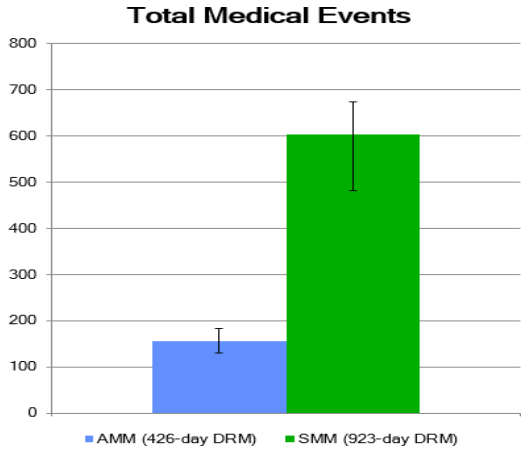

Figure 1: Average Total Medical Events predicted by IMM for AMM (426-day) and SMM (923-day) missions.

4.1.2 Crew Health Index

In simple terms, CHI is a rough estimate of how much crew performance is likely to decrease as a result of medical conditions that occur. There is no clear way to predict when decrements in CHI would lead to Loss of Mission Objectives, but as CHI decreases, the risk of Loss of Mission Objectives increases. CHI is a calculated percentage using quality-adjusted mission time lost (QAMTL) due to in-flight medical events and resources available to treat those conditions. It is shown in percent values and ranges from 0-100, where zero represents complete crew impairment and 100 represents a completely functional crew. Figure 2 shows the difference in CHI for AMM and SMM comparison.

	CHI	95% CI	
AMM	91.56	75.87	97.76
SMM	72.52	56.33	84.24

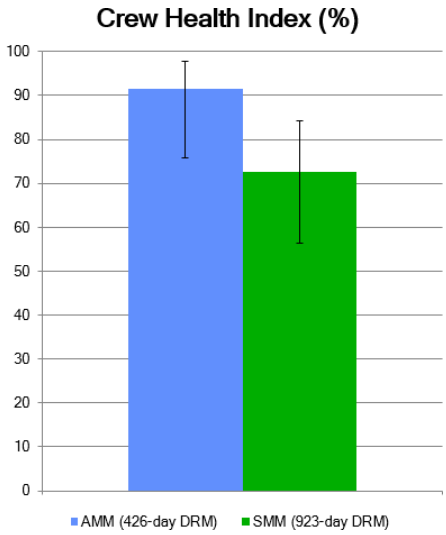

Figure 2: Average CHI is a function of quality time lost and mission duration and is a proxy value for expected performance range for crews.

4.1.2.1 Mission Level Outcomes

Mission Level Outcomes include calculating the likelihood of reaching EVAC or LOCL. Table 1 shows numerical values for the probability of EVAC and LOCL.

Table 1: Probability of reaching EVAC criteria or LOCL based on medical conditions modeling for an AMM and SMM.

	EVAC			LOCL		
	Probability	95% CI		Probability	95% CI	
AMM	0.0625	0.0610	0.0641	0.0057	0.0053	0.0062
SMM	0.2940	0.2911	0.2967	0.0158	0.0151	0.0166

Figure 3 below shows a graphical representation of these probabilities divided into types of medical conditions that contributed to the outcomes. “Environmental” includes illnesses caused by exposure to hazards in the vehicle or space environment such as smoke inhalation, toxic exposures, decompression sickness, and others. “Injury/Trauma” includes traumatic injuries more likely to be experienced on the planetary surface like musculoskeletal injuries, bleeding injuries, etc. “Medical” includes conditions that arise simply out of being human such as infections, appendicitis, etc. Likelihood of EVAC and LOCL are significantly reduced in an AMM scenario across all categories.

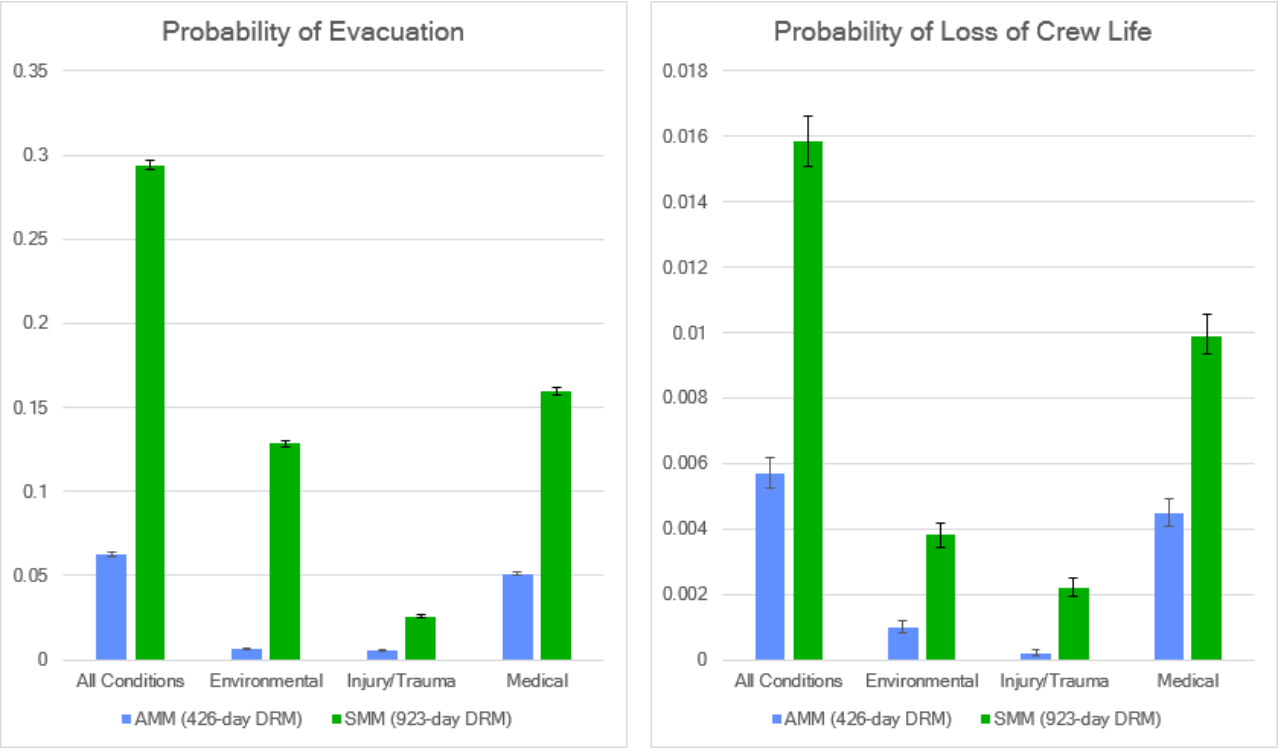

Figure 3: Left: Probability of Evacuation criteria met expressed by types of medical conditions and Right: Probability of LOCL criteria met expressed by types of medical conditions.

4.2 Integrated Medical Model Summary

- Average number of Total Medical Events (TME) [lower is better]:
  - AMM (426-day): 156.45 events.
  - SMM (923-day): 603.03 events.
- Average CHI [higher is better]:
  - AMM (426-day): 91.56.
  - SMM (923-day): 72.52.
- Probability of consideration for EVAC [lower is better]:
  - AMM (426-day): 0.0625.
  - SMM (923-day): 0.2940.
- Probability of LOCL [lower is better]:
  - AMM (426-day): 0.0057.
  - SMM (923-day): 0.0158.

5 Space Radiation Model

5.1 Background

Long-term health impacts for crew on a Mars mission are not predicted by the IMM. The SRAG at the JSC considered the duration of transit and planetary phases and estimated radiation environmental exposures from existing data to calculate the excess risk that an astronaut will die from a radiation-induced cancer in their lifetime. Solar Max was assumed. The metric calculated is called Radiation Exposure Induced Death (REID) and is expressed as a percentage (%) of increased likelihood of death due to cancer above an estimated population baseline level. Radiation risks are heavily dependent on both mission (e.g. timing, duration, vehicle shielding) and astronaut (sex and age) parameters. Furthermore, due to the many uncertainties in the involved parameters, these numbers should also be taken as a ballpark estimate.

5.2 Key Results

Results were calculated for four cases: 45-year-old female and male 'Rookie' astronauts (no prior radiation exposure from spaceflight) and 55-year-old female and male 'Veteran' astronauts (179-day prior radiation exposure from an ISS mission-level exposure).

For a 45-year-old female astronaut who has no prior flights, the SMM results in a 1.9% REID calculated at the mean. Current NASA medical standards limit radiation risk to below 3% REID at the 97.5% confidence level. At the 97.5% confidence level, this exemplar astronaut would carry 5.4% REID risk, which exceeds current standards. For comparison, using the same 45-year-old female astronaut who has no prior flights, the AMM results in a 1.2% REID at the mean and 3.6% REID at the 97.5% confidence level. Thus, the trip would still violate existing standards, but the ballpark risk is approximately 60% less than the SMM. Figure 4 below graphically depicts this for the reference case. For more detail and for considerations of male crew and veteran crew, please see Appendix 2 below.

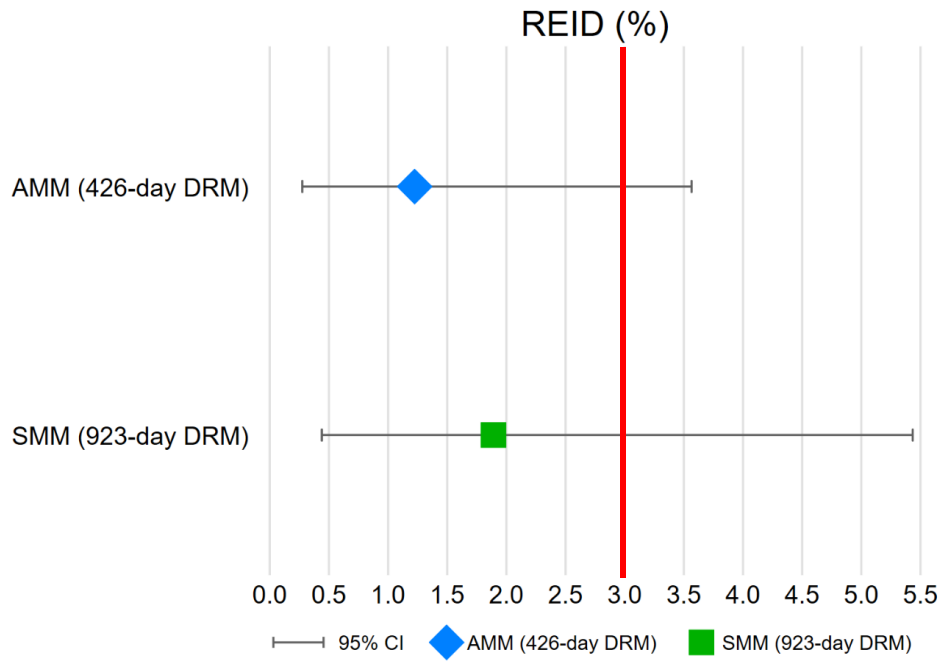

Figure 4: Visualization of the estimated REID calculated at the Mean and showing the associated 95% confidence intervals (CIs). Current NASA standards protect to less than 3% excess risk at the upper 95% CI. Any extension of the CIs beyond the red line exceeds current NASA standards.

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7 Appendix 1

This appendix describes the input parameters and modeling assumptions that inform the data shown in key results. It is provided for completeness sake in this appendix for reference. This information includes a description of Crew Characteristics, Model Modifications, high-level Modeling Approach, list of Lockdown changes for these runs, and lists of driving conditions for EVAC and LOCL.

7.1 Crew Characteristics

Standard modeling procedure is to make assumptions about crew factors that can predispose to them to additional medical risk. Table 2 shows the assumed crew characteristics. Note that IMM does not consider age in its simulations. The data used is a compilation of all ages included in the evidence base. Therefore, the crew descriptors chosen by SRAG for the Long-Term Health calculations in Appendix 2 are comparable for the purposes of this study. These apply to the calculations for both missions.

Table 2: Crew characteristics for both missions.

426 and 923 Day DRMs	Sex	Crowns	EVA	CAC – Coronary Artery Calcium Score	Contacts	Prior Abdominal Surgery
Crew 1	Male	Yes	Yes	No	No	No
Crew 2	Male	No	Yes	Yes	No	No
Crew 3	Female	No	Yes	No	Yes	No
Crew 4	Female	No	Yes	No	No	Yes

S-20200303-423, Long Duration Risk Posture

7.2 Model Modifications

Due to limited vehicle size consisting of a single module and limited movement of crew during flight, the following major traumatic injury conditions are judged highly unlikely to occur during flight for the DRMs. However, these conditions were deemed possible during the specified EVA windows.

The IMM is baselined to ISS and does not simulate EVAs in partial-gravity environments. For this service request, in accordance with the assumption that crew members would perform EVAs in

partial gravity environments, the set of conditions listed below were invalidated outside the requested EVA windows (i.e. could only occur during the EVAs).

- Abdominal Injury
- Acute Compartment Syndrome
- Barotrauma
- Chest Injury
- Elbow Dislocation
- Head Injury
- Hip/Proximal Femur Fracture
- Lower Extremity (LE) Stress Fracture
- Lumbar Spine Fracture
- Shoulder Dislocation
- Neurogenic Shock
- Traumatic Hypovolemic Shock

Rather than considering the entire ISS volume for application of Fire Model result input to the IMM, ISS Node 3 was used to approximate the size of the Orion vehicle. The corresponding Node 3 Fire Model results (directly from the ISS Probabilistic Risk Assessment (PRA) Fire Model v3.2) were used to update Burns Secondary to Fire and Smoke Inhalation for this request as follows:

- Burns Secondary to Fire:
  - **incidence 0.00613 (events/person year)** - probability one or more crew exposed to response-level event (value same as for likelihood for Fire Sustains (response-level event) since modeling for single compartment, i.e. Node 3) (v3.2);
  - **worst-case scenario = 0-5%** - EVAC (uncontrollable fire - not vehicle) (value = 0.0486; derived from uncontrolled fire event/probability one or more crew exposed to response-level event)
- Smoke Inhalation:
  - **incidence 0.00613 (events/person year)** - Fire Sustains (response-level event) (v3.2);
  - **worst case scenario = 0-5%** - EVAC (uncontrollable fire - not vehicle) (value = 0.0486; derived from uncontrolled fire event/Fire Sustains (response-level event))

7.3 Modeling Approach

- 100,000 trials, where each trial can be considered an individual “mission”
- ISS MedCap Scenario (ISS available resources without resupply)
- CHI = (1- (QAMTL ÷ Mission Length)) x 100

- QAMTL is determined by summing the product of functional impairment and duration for all three clinical phases of that condition
- Probability of EVAC in the context of IMM means that medical evacuation from the ISS would be considered for definitive treatment of the afflicted crew member(s). EVAC is considered an end-state result if any of the following criteria are met: 1) potential LOCL; 2) potential significant permanent impairment; or 3) potential intractable pain.
- LOCL in the context of IMM should be interpreted to mean that the clinical scenario resulted in death of the affected crew member(s).

7.4 List of Lockdown 61 Integrated Medical Evidence Database (iMED) Changes

- Inclusion of Real World System updates from ISS Expeditions 14 through 39/40 and Shuttle Transportation System (STS) missions 114 through 135.
- Updates to Best- and Worst-Case probabilities to ranges (from single integers)
- Updated Corneal Ulcer worst-case probability from 0-50% to 0-2%.
- Updated Incidence for Eye Chemical Burn (to reflect decreased incidence due to removing the influence of EVA helmet surfactant from Shuttle missions)
- Updated Spaceflight Induced Intracranial Pressure/Vision Alterations (VIIP/SANS): The currently known worst-case finding is significant disc edema that would result in consideration of evacuation. Research continues to inform and update this condition.
  - Updated worst-case probability (from 20% to 12.19-14.63%)
  - Remove Diamox from VIIP resources (not used for VIIP treatment)
  - Update the current iMED estimate of probability of EVAC for VIIP using Subject Matter Expert (SME) opinion (from 0-21% to 0-1%)

7.5 Medical Evacuation and Loss of Crew Life Driving Conditions

Table 3: Driving conditions for reaching consideration of evacuation criteria for an AMM (426 days with 30 days of EVA) with the total number of times that condition drove an EVAC event per 100,000 simulations. 'Per Trial' and '1 in X trials' show the odds for a single mission.

Highlighted Conditions are those linked to EVA.

EVAC, AMM with 30 4-person EVAs	Total	per Trial	1 in X trials
HERPES ZOSTER REACTIVATION (SHINGLES)	1157	0.01157	86
NEPHROLITHIASIS	767	0.00767	130
DENTAL ABSCESS	515	0.00515	194
URINARY TRACT INFECTION	419	0.00419	239
SEPSIS	416	0.00416	240

EVAC, AMM with 30 4-person EVAs	Total	per Trial	1 in X trials
EYE CHEMICAL BURN	316	0.00316	316
STROKE (CEREBROVASCULAR ACCIDENT)	309	0.00309	324
SMALL BOWEL OBSTRUCTION	292	0.00292	342
WRIST FRACTURE	205	0.00205	488
SKIN LACERATION	189	0.00189	529
SEIZURES	142	0.00142	704
ATRIAL FIBRILLATION/ ATRIAL FLUTTER	132	0.00132	758
APPENDICITIS	128	0.00128	781
ANGINA/MYOCARDIAL INFARCTION	126	0.00126	794
HEADACHE (CO_2 INDUCED)	104	0.00104	962
TOXIC EXPOSURE (AMMONIA)	87	0.00087	1149
DENTAL EXPOSED PULP	82	0.00082	1220
ACUTE DIVERTICULITIS	81	0.00081	1235
EYE INFECTION	81	0.00081	1235
BURNS SECONDARY TO FIRE	72	0.00072	1389
INDIGESTION	67	0.00067	1493
EYE CORNEAL ULCER	58	0.00058	1724
RETINAL DETACHMENT	51	0.00051	1961
VISUAL IMPAIRMENT AND/OR INCREASED INTRACRANIAL PRESSURE (VIIP)(SPACE ADAPTATION)	51	0.00051	1961
ACUTE CHOLECYSTITIS/BILIARY COLIC	50	0.0005	2000
MEDICATION OVERDOSE/ADVERSE REACTION	49	0.00049	2041
NECK SPRAIN/STRAIN	42	0.00042	2381
ABDOMINAL WALL HERNIA	33	0.00033	3030
EYE IRRITATION/ABRASION	32	0.00032	3125
DIARRHEA	31	0.00031	3226
DECOMPRESSION SICKNESS SECONDARY TO EXTRAVEHICULAR ACTIVITY	30	0.0003	3333
RESPIRATORY INFECTION	29	0.00029	3448
OTITIS MEDIA	26	0.00026	3846
SKIN INFECTION	26	0.00026	3846
ACUTE SINUSITIS	24	0.00024	4167
SMOKE INHALATION	22	0.00022	4545
ACUTE PANCREATITIS	21	0.00021	4762
GASTROENTERITIS	21	0.00021	4762
BACK SPRAIN/STRAIN	19	0.00019	5263
TRAUMATIC HYPOVOLEMIC SHOCK	19	0.00019	5263
CHOKING/OBSTRUCTED AIRWAY	16	0.00016	6250
LOWER EXTREMITY (LE) STRESS FRACTURE	15	0.00015	6667

EVAC, AMM with 30 4-person EVAs	Total	per Trial	1 in X trials
URINARY RETENTION (SPACE ADAPTATION)	10	0.0001	10000
CHEST INJURY	8	0.00008	12500
OTITIS EXTERNA	8	0.00008	12500
ACUTE ARTHRITIS	7	0.00007	14286
ACUTE ANGLE-CLOSURE GLAUCOMA	6	0.00006	16667
HEAD INJURY	6	0.00006	16667
DEPRESSION	5	0.00005	20000
EYE PENETRATION (FOREIGN BODY)	5	0.00005	20000
HIP SPRAIN/STRAIN	5	0.00005	20000
HIP/PROXIMAL FEMUR FRACTURE	5	0.00005	20000
HYPERTENSION	5	0.00005	20000
SUDDEN CARDIAC ARREST	5	0.00005	20000
SKIN INFECTION	4	0.00004	25000
ACUTE RADIATION SYNDROME	4	0.00004	25000
SKIN RASH	4	0.00004	25000
CARDIOGENIC SHOCK SECONDARY TO MYOCARDIAL INFARCTION	3	0.00003	33333
NOSE BLEED (SPACE ADAPTATION)	3	0.00003	33333
ACUTE PROSTATITIS	2	0.00002	50000
KNEE SPRAIN/STRAIN	2	0.00002	50000
SHOULDER DISLOCATION	2	0.00002	50000
ABDOMINAL INJURY	1	0.00001	100000
ACUTE COMPARTMENT SYNDROME	1	0.00001	100000
ALTITUDE SICKNESS	1	0.00001	100000
ANKLE SPRAIN/STRAIN	1	0.00001	100000
ANXIETY	1	0.00001	100000
LUMBAR SPINE FRACTURE	1	0.00001	100000
SHOULDER SPRAIN/STRAIN	1	0.00001	100000
WRIST SPRAIN/STRAIN	1	0.00001	100000

Conditions Invalidated Outside of EVAs that did NOT result in EVAC: Barotrauma, Elbow Dislocation, Neurogenic Shock

EVA-specific conditions that did NOT result in EVAC: Fingernail Delamination Secondary to EVA, Paresthesias Secondary to EVA

Table 4: Driving conditions for reaching consideration of evacuation criteria for SMM (923 days with 401 days of EVA) with the total number of times that condition drove an EVAC event per 100,000 simulations. 'Per Trial' and '1 in X trials' show the odds for a single mission. Highlighted Conditions are those linked to EVA

EVAC, SMM with 401 4-person EVAs	Total	per Trial	1 in X trials
DECOMPRESSION SICKNESS SECONDARY TO EXTRAVEHICULAR ACTIVITY	10976	0.10976	9
HERPES ZOSTER REACTIVATION (SHINGLES)	4194	0.04194	24
URINARY TRACT INFECTION	2924	0.02924	34
EYE CHEMICAL BURN	2434	0.02434	41
NEPHROLITHIASIS	1691	0.01691	59
DENTAL ABSCESS	1241	0.01241	81
EYE INFECTION	892	0.00892	112
SEPSIS	848	0.00848	118
EYE CORNEAL ULCER	652	0.00652	153
STROKE (CEREBROVASCULAR ACCIDENT)	647	0.00647	155
SKIN LACERATION	629	0.00629	159
SMALL BOWEL OBSTRUCTION	623	0.00623	161
WRIST FRACTURE	492	0.00492	203
ANGINA/MYOCARDIAL INFARCTION	333	0.00333	300
APPENDICITIS	319	0.00319	313
DENTAL EXPOSED PULP	311	0.00311	322
ACUTE DIVERTICULITIS	279	0.00279	358
NECK SPRAIN/STRAIN	277	0.00277	361
HEADACHE (CO_2 INDUCED)	276	0.00276	362
SEIZURES	272	0.00272	368
ATRIAL FIBRILLATION/ ATRIAL FLUTTER	268	0.00268	373
EYE IRRITATION/ABRASION	266	0.00266	376
LOWER EXTREMITY (LE) STRESS FRACTURE	265	0.00265	377
TRAUMATIC HYPOVOLEMIC SHOCK	193	0.00193	518
ACUTE ARTHRITIS	183	0.00183	546
TOXIC EXPOSURE (AMMONIA)	166	0.00166	602
INDIGESTION	164	0.00164	610
BURNS SECONDARY TO FIRE	157	0.00157	637
BACK SPRAIN/STRAIN	150	0.0015	667
HEAD INJURY	130	0.0013	769
SKIN RASH	126	0.00126	794
ACUTE CHOLECYSTITIS/BILIARY COLIC	115	0.00115	870
DIARRHEA	113	0.00113	885
SKIN INFECTION	112	0.00112	893
RETINAL DETACHMENT	100	0.001	1000

EVAC, SMM with 401 4-person EVAs	Total	per Trial	1 in X trials
MEDICATION OVERDOSE/ADVERSE REACTION	91	0.00091	1099
OTITIS MEDIA	78	0.00078	1282
ACUTE SINUSITIS	76	0.00076	1316
GASTROENTERITIS	64	0.00064	1563
ACUTE PANCREATITIS	62	0.00062	1613
HIP/PROXIMAL FEMUR FRACTURE	62	0.00062	1613
RESPIRATORY INFECTION	62	0.00062	1613
VISUAL IMPAIRMENT AND/OR INCREASED INTRACRANIAL PRESSURE (VIIP)(SPACE ADAPTATION)	52	0.00052	1923
ABDOMINAL WALL HERNIA	49	0.00049	2041
SMOKE INHALATION	39	0.00039	2564
OTITIS EXTERNA	38	0.00038	2632
CHOKING/OBSTRUCTED AIRWAY	29	0.00029	3448
DEPRESSION	25	0.00025	4000
CHEST INJURY	24	0.00024	4167
ACUTE ANGLE-CLOSURE GLAUCOMA	22	0.00022	4545
HIP SPRAIN/STRAIN	22	0.00022	4545
LUMBAR SPINE FRACTURE	22	0.00022	4545
ABDOMINAL INJURY	20	0.0002	5000
ACUTE RADIATION SYNDROME	18	0.00018	5556
ACUTE COMPARTMENT SYNDROME	15	0.00015	6667
SHOULDER DISLOCATION	14	0.00014	7143
HYPERTENSION	11	0.00011	9091
ELBOW SPRAIN/STRAIN	10	0.0001	10000
ACUTE PROSTATITIS	9	0.00009	11111
CARDIOGENIC SHOCK SECONDARY TO MYOCARDIAL INFARCTION	8	0.00008	12500
FINGER DISLOCATION	8	0.00008	12500
SUDDEN CARDIAC ARREST	8	0.00008	12500
EYE PENETRATION (FOREIGN BODY)	6	0.00006	16667
ELBOW DISLOCATION	5	0.00005	20000
URINARY RETENTION (SPACE ADAPTATION)	5	0.00005	20000
ANXIETY	4	0.00004	25000
KNEE SPRAIN/STRAIN	4	0.00004	25000
ANAPHYLAXIS	3	0.00003	33333
ANKLE SPRAIN/STRAIN	2	0.00002	50000
NOSE BLEED (SPACE ADAPTATION)	2	0.00002	50000
SHOULDER SPRAIN/STRAIN	1	0.00001	100000
WRIST SPRAIN/STRAIN	1	0.00001	100000

Conditions Invalidated Outside of EVAs that did NOT result in EVAC: Barotrauma, Neurogenic Shock

EVA-specific conditions that did NOT result in EVAC: Fingernail Delamination Secondary to EVA, Paresthesias Secondary to EVA

Note: The high contribution of Decompression Sickness secondary to EVA is reflective of the atmospheric pressure, constituents, and pre-breathe protocols used in ISS. The risk would change if Exploration Atmospheric changes and pre-breathe protocols are used in a Mars mission.

7.6 Driving Conditions for Loss of Crew Life

Table 5: Driving conditions for reaching LOCL criteria for an AMM (426 days with 30 days of EVA) with the total number of times that condition drove an LOCL event per 100,000 simulations. 'Per Trial' and '1 in X trials' show the odds for a single mission. Highlighted Conditions are those linked to EVA.

LOCL, AMM with 30 4-person EVAs	Total	per Trial	1 in X trials
SEPSIS	206	0.00206	485
STROKE (CEREBROVASCULAR ACCIDENT)	122	0.00122	820
MEDICATION OVERDOSE/ADVERSE REACTION	47	0.00047	2128
TOXIC EXPOSURE (AMMONIA)	47	0.00047	2128
APPENDICITIS	39	0.00039	2564
BURNS SECONDARY TO FIRE	37	0.00037	2703
SUDDEN CARDIAC ARREST	22	0.00022	4545
CHEST INJURY	9	0.00009	11111
DECOMPRESSION SICKNESS SECONDARY TO EXTRAVEHICULAR ACTIVITY	8	0.00008	12500
TRAUMATIC HYPOVOLEMIC SHOCK	8	0.00008	12500
SMOKE INHALATION	5	0.00005	20000
ACUTE DIVERTICULITIS	4	0.00004	25000
CARDIOGENIC SHOCK SECONDARY TO MYOCARDIAL INFARCTION	3	0.00003	33333
SMALL BOWEL OBSTRUCTION	3	0.00003	33333
ACUTE PANCREATITIS	2	0.00002	50000
ACUTE RADIATION SYNDROME	2	0.00002	50000
HEAD INJURY	2	0.00002	50000
ABDOMINAL INJURY	1	0.00001	100000
ABDOMINAL WALL HERNIA	1	0.00001	100000
ALTITUDE SICKNESS	1	0.00001	100000
CHOKING/OBSTRUCTED AIRWAY	1	0.00001	100000

Conditions Invalidated Outside of EVAs that did NOT result in LOCL: Acute Compartment Syndrome, Barotrauma, Elbow Dislocation, Hip/Proximal Femur Fracture, Lower Extremity Stress Fracture, Lumbar Spine Fracture, Shoulder Dislocation, Neurogenic Shock

EVA-specific conditions that did NOT result in LOCL: Fingernail Delamination Secondary to EVA, Paresthesias Secondary to EVA

Table 6: Driving conditions for reaching LOCL for SMM (923 days with 401 days of EVA) with the total number of times that condition drove an LOCL event per 100,000 simulations. 'Per Trial' and '1 in X trials' show the odds for a single mission. Highlighted Conditions are those linked to EVA.

LOCL, SMM with 401 4-person EVAs	Total	per Trial	1 in X trials
SEPSIS	435	0.00435	230
STROKE (CEREBROVASCULAR ACCIDENT)	251	0.00251	398
DECOMPRESSION SICKNESS SECONDARY TO EXTRAVEHICULAR ACTIVITY	215	0.00215	465
APPENDICITIS	125	0.00125	800
TRAUMATIC HYPOVOLEMIC SHOCK	107	0.00107	935
MEDICATION OVERDOSE/ADVERSE REACTION	99	0.00099	1010
TOXIC EXPOSURE (AMMONIA)	87	0.00087	1149
HEAD INJURY	67	0.00067	1493
BURNS SECONDARY TO FIRE	63	0.00063	1587
SUDDEN CARDIAC ARREST	36	0.00036	2778
CHEST INJURY	33	0.00033	3030
ACUTE DIVERTICULITIS	15	0.00015	6667
ABDOMINAL INJURY	13	0.00013	7692
SMOKE INHALATION	9	0.00009	11111
ACUTE RADIATION SYNDROME	8	0.00008	12500
SMALL BOWEL OBSTRUCTION	8	0.00008	12500
CARDIOGENIC SHOCK SECONDARY TO MYOCARDIAL INFARCTION	7	0.00007	14286
CHOKING/OBSTRUCTED AIRWAY	7	0.00007	14286
ANAPHYLAXIS	4	0.00004	25000
ABDOMINAL WALL HERNIA	3	0.00003	33333
ACUTE PANCREATITIS	2	0.00002	50000
SEIZURES	2	0.00002	50000
NEUROGENIC SHOCK	1	0.00001	100000

Conditions Invalidated Outside of EVAs that did NOT result in LOCL: Acute Compartment Syndrome, Barotrauma, Elbow Dislocation, Hip/Proximal Femur Fracture, Lumbar Spine Fracture, Shoulder Dislocation

EVA-specific conditions that did NOT result in LOCL: Fingernail Delamination Secondary to EVA, Paresthesias Secondary to EVA

Note: The high contribution of Decompression Sickness secondary to EVA is reflective of the atmospheric pressure, constituents, and pre-breathe protocols used in ISS. The risk would change if Exploration Atmospheric changes and pre-breathe protocols are used in a Mars mission.

8 Appendix 2

Table 7 in this appendix shows information regarding excess risk associated with radiation exposure based on the estimated radiation environment and the SRAG model for calculating cancer risk.

Calculations were available for an 890-day mission, which is used here for the SMM for the purposes of calculating risk differences. Radiation estimates with cancer risk are expressed as % REID. “Rookie Cases” assume that the astronaut has had no prior spaceflight exposure. “Veteran Cases” assume one 179-day ISS mission of prior exposure. REID is shown at the mean (Mn), which is the best descriptor of crew member risk, and at other confidence levels. The current medical standard protects crews to 3% REID at the upper 95th%confidence level.

Therefore, any total mission exposure at the upper 95th% confidence level would exceed current medical standards in both of the missions examined.

Table 7: Calculations for REID for Male and Female rookie and veteran astronauts shown by flight segment and total mission duration for comparison.

45 year old female rookie						
Mars standard mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Flight to Mars	207	159.2	0.6	1.5	1.9	0.5
Stay on Mars	475	165.6	0.6	1.5	1.9	0.5
Flight home	208	160.1	0.6	1.5	1.8	0.5
Total mission	890	484.9	1.9	4.4	5.4	1.5
Mars accelerated mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Flight to Mars	180	138.7	0.5	1.3	1.6	0.4
Stay on Mars	30	10.5	0.04	0.098	0.122	0.03
Flight home	210	161.6	0.6	1.5	1.9	0.5
Total mission	420	310.8	1.2	2.9	3.6	1
45 year old male rookie						
Mars standard mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Flight to Mars	207	156.8	0.5	1.1	1.3	0.4
Stay on Mars	475	164.1	0.5	1.1	1.4	0.4
Flight home	208	157.4	0.5	1.0	1.3	0.4
Total mission	890	478.3	1.4	3.1	3.8	1.1
Mars accelerated mission duriong solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Flight to Mars	180	136.4	0.4	0.9	1.1	0.3
Stay on Mars	30	10.3	0.03	0.07	0.09	0.02
Flight home	210	158.9	0.5	1.1	1.3	0.4
Total mission	420	305.6	0.9	2.0	2.5	0.7
55 year old female veteran						
Mars standard mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Previous ISS mission @ 50yo	179	58.5	0.2	0.5	0.7	0.2
Flight to Mars	207	159.2	0.6	1.4	1.7	0.4
Stay on Mars	475	165.6	0.6	1.4	1.7	0.4
Flight home	208	160.1	0.5	1.3	1.6	0.4
Total mission	1069	543.4	1.9	4.4	5.4	1.5
Mars accelerated mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Previous ISS mission @ 50yo	179	28.5	0.2	0.5	0.7	0.2
Flight to Mars	180	138.7	0.5	1.2	1.4	0.4
Stay on Mars	30	10.5	0.04	0.09	0.11	0.03
Flight home	210	161.6	0.6	1.3	1.7	0.4
Total mission	599	339.3	1.3	3.1	3.8	1.0
55 year old male veteran						
Mars standard mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Previous ISS mission @ 50yo	179	56.2	0.2	0.4	0.5	0.1
Flight to Mars	207	156.8	0.4	1.0	1.2	0.3
Stay on Mars	475	164.1	0.4	1.0	1.2	0.3
Flight home	208	157.4	0.4	0.9	1.2	0.3
Total mission	1069	534.5	1.4	3.2	3.9	1.1
Mars accelerated mission during solar max						
Mission details:	Duration (Days)	Mn Colon Eq dose (mSv)	Mn REID (%)	95th %ile REID (%)	97.5th %ile REID (%)	Median
Previous ISS mission @ 50yo	179	56.2	0.2	0.4	0.5	0.1
Flight to Mars	180	136.4	0.4	0.8	1.0	0.3
Stay on Mars	30	10.3	0.03	0.06	0.08	0.02
Flight home	210	158.9	0.4	1.0	1.2	0.3
Total mission	599	361.8	1.0	2.2	2.7	0.8

9 Acronyms and Abbreviations

AMM	Accelerated Mars Mission
CHI	Crew Health Index
CI	Confidence Interval
DRM	Design Reference Mission
EVA	Extravehicular Activity
EVAC	medical evacuation
iMED	Integrated Medical Evidence Database
IMM	Integrated Medical Model
ISS	International Space Station
JSC	Johnson Space Center
LE	Lower Extremity
LEO	low Earth orbit
LOCL	Loss of Crew Life
LOMO	Loss of Mission Objectives
Mn	mean
NSCR	NASA Space Radiation Cancer Risk Model
PRA	Probabilistic Risk Assessment
QAMTL	quality-adjusted mission time lost
REID	Radiation Exposure Induced Death
SME	Subject Matter Expert
SMM	Standard Mars Mission
SMOCB	Space Medicine Operations Control Board
SRAG	Space Radiation Analysis Group
STS	Shuttle Transportation System
TME	Total Medical Events
VIIP/SANS	Spaceflight Induced Intracranial Pressure/Vision Alterations