HUMANS TO MARS, BUT HOW MANY? USING TRAINING QUALIFICATION MODELING TO INFORM NUMBER OF CREW

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ABSTRACT

Missions to Mars will differ from all previous human spaceflight missions in that the crew of astronauts will be required to operate in an Earth-independent manner due to the long communication delays, making the decision on crew size critical to mission success. To support National Aeronautics and Space Administration (NASA) decision makers, NASA's Engineering and Safety Center (NESC) developed a quantitative methodology for assessing the number of crew necessary to meet primary mission objectives and respond to unforeseen failures based on modeling of NASA's crew training qualifications. We present results of a custom-built model of a Mars crew qualification and responsibility matrix (CQRM) and discuss the implications on trade space analysis of Mars mission crew size.

1. BACKGROUND

How many people should NASA send to Mars? Almost from the very beginning of Mars mission studies, there has been an awareness that to determine the necessary crew size, planners must consider crewmembers' roles and tasks along with the need for cross-training to provide backup in case of contingencies. Nonetheless, there has not been a detailed, quantitative analysis of crew tasking, workload, and expertise for Mars missions [1]. However, it is inescapable that a mismatch between the crew size and their workload, and the level of expertise they must possess to handle unforeseen failures, increases risk to mission success and crew safety.

Without a process to determine the number and composition of crew necessary to successfully accomplish Mars missions, NASA increases the risk that crew sizes may be too small to meet primary mission objectives under nominal conditions and, more consequentially, that crewmembers may not have the expertise needed to successfully respond to unforeseen failures without the real-time expertise of the Mission Control Central (MCC) teams NASA currently relies upon.

To fill this gap in NASA's capability for determining crew size for missions to Mars, the NESC developed a methodology for NASA to perform systematic, repeatable trade space analysis comparing crew size against trade space dimensions, using quantitative data from human performance modeling [2].

This capability was developed out of a recognition that a Mars crew will be denied real-time support from the MCC, owing to the distance-induced communication delay/blackout with Earth (e.g., up to ~22 minutes one-way and ~2 to 3 weeks each mission). This fundamental constraint, which is unprecedented in the history of human spaceflight, brings a new appreciation for what the term "crew" encompasses. In every previous NASA program, the onboard flight crew has relied on the combined intellects and energies of experts in the flight control room and its back rooms on the ground comprising, in essence, additional crewmembers to help meet primary mission objectives and respond to unforeseen anomalies.

On a Mars mission astronauts making real-time decisions about how to accomplish primary mission objectives (i.e., during surface extravehicular activities (EVAs)) or how to respond to unforeseen, time-critical failures will have to rely on their knowledge when using decision-support systems, whose information would be limited to scenarios that were anticipated before the mission. The NESC methodology provides a data-driven means of assessing, based on today's limited understanding of Mars vehicle systems, whether the capabilities that would exist within a given crew size would be adequate to accomplish mission objectives and successfully respond to unforeseen failures, for which procedures would not exist, with potential loss of crew/loss of mission consequences and short time-to-effect.

The NESC's quantitative methodology fills a longstanding gap in the tools for designing Mars missions. In the past, crew size determinations have been based on a limited, mostly non-quantitative understanding of the impact of crew workload on mission success and crew survival. Now, in weighing the question of whether a given crew size is adequate to ensure crew survival and mission success, decision makers can be guided by a systematic, quantitative analysis.

2. METHODOLOGY

The methodology for trade space analysis is comprised of several steps:

- Gather Mars Mission Information
- Determine Use Cases to Model
- Create a Trade Space Evaluation Framework
- Conduct Human Performance Modeling
- Perform Trade Space Analysis

The results of the analysis can be used to make recommendations to decision makers as they consider the potentially competing factors in deciding on the crew size for missions to Mars. This methodology is based on work performed for the United States Army [3] and informed by human performance modeling conducted by the Naval Postgraduate School. This paper focuses on one of the four human performance models built by the NESC for trade space analysis, a model based on training qualifications named the Personnel, Expertise, and Training model. Reference [2] provides further details on the methodology, including the trade space evaluation framework.

3. PERSONNEL, EXPERTISE, AND TRAINING MODEL

Based on International Space Station (ISS) historical data, there is a very high likelihood of unforeseen failures with loss of crew/loss of mission potential and short time-to-effect that could lead to actual loss of crew/loss of mission outcomes. The assumption by NASA's Earth Independent Human System Operations Risk team is that an unforeseen failure that must be safed within ~24 hours and up to ~72 hours will require the Mars crew to respond independently from the MCC given the communications delay/blackout with Earth.

If unforeseen failures were to occur on a mission to Mars, it will be critical that the crew have the necessary level of expertise to accurately diagnose lost functionality, to safe vehicle systems and payloads and/or to reconfigure systems if necessary to prevent cascading failures, and to restore critical functionality. This will require crewmembers to have "an understanding of how systems work, an understanding of the rationale behind flight rules, and critical thinking skills to make informed decisions when responding to urgent, unanticipated anomalies" [4]. Additionally, crewmembers will require expertise to support root cause diagnostic troubleshooting and formulating a repair plan in conjunction with the ground [5].

The Personnel, Expertise, and Training model was designed to provide the capability to consider the trade space of crew size and level of expertise in the real-time environment, where the crew's expertise is necessary both for accomplishing primary mission objectives and as a component for mitigating the risk of these unforeseen failures.

3.1 Crew Qualifications and Responsibilities

To consider the necessary expertise within a Mars crew, the team selected a Mars design reference mission for their analysis. The selected mission has five vehicles in the architecture. The crew launches from Earth in an Orion Multipurpose Crew Vehicle (MPCV) spacecraft and transits from Earth to Mars in the Transit Habitat. A subset of the crew descends to the planetary surface in the Mars Descent Vehicle (MDV), lives and works on the surface in the Mars Rover, and returns to Mars orbit in the Mars Ascent Vehicle (MAV). The crew then returns to Earth orbit in the Transit Habitat and descends to Earth in an Orion spacecraft.

Using ISS designations to create a Generic Mars CQRM, the team identified roles and responsibilities as applicable to each of the five vehicles [5]. Roles included commander (CDR), mission specialist [MS] and flight engineer (FE), as well as expeditionary team member (E) [6]. Responsibilities, included piloting (PLT), emergency response (Emer), activation/deactivation, logistics (including inventory and stowage), vehicle system operations (environmental control and life support system (ECLSS), thermal control system (TCS), command and data handling (CDH), local area network (LAN), communication and tracking (C&T), electrical power system (EPS), motion control system (MCS), propulsion (Prop)), structures and mechanisms (Struc & Mech), intravehicular activity (IVA) maintenance (Maint) and repair, habitability, imagery/video, crew medical officer (CMO) response, robotics operations including EVA robotics and track and capture, medical operations (Med Ops), EVA operations, and transit and planetary surface research payloads.

Table 1 lists Mars mission qualifications applicable to each vehicle in the design reference mission, adapted for Mars from ISS qualifications developed by the ISS International Partners [5]. The team determined the recommended number of crew qualifications for each area of responsibility necessary for a Mars mission (e.g., two system leads for each system) and documented this in a Generic Mars CQRM for each of the vehicles. Table 2 shows the Generic Mars CQRM for the Transit Habitat. Reference [2] shows the Generic Mars CQRM for all five vehicles.

3.2 Training Flow Hours

The Generic Mars CQRM reflects the qualification levels achieved in training. To model a flight-assigned Mars CQRM that balances the training workload across a crew,

Table 1. Crew Qualifications for Missions to Mars [5, 6]

Qualification	Designation	Description
MPCV, Mars Descent Vehicle (MDV), and Mars Ascent Vehicle (MAV)		
Commander	CDR	The commander title does not infer specific qualifications or responsibilities with respect to vehicle systems, but rather represents a chain of command with respect to the vehicle. All other crewmembers onboard work under the command of the vehicle commander.
Mission Specialist	MS	A mission specialist has the capability to support mission operations and live safely on-board the vehicle. This includes but is not limited to emergency response for each vehicle and all habitability duties for each vehicle.
Pilot	PLT	A pilot has the capability to live safely on-board the vehicle and to perform mission critical tasks including ascent/entry and docking piloting tasks and respond to off-nominal events and unforeseen failures. MDV and MAV pilots have the additional capability to perform activation/deactivation of the vehicles.
Mars Transit Habitat and Mars Rover		
Commander	CDR	The commander title does not infer specific qualifications or responsibilities with respect to vehicle systems, but rather represents a chain of command with respect to the vehicle. All other crewmembers onboard work under the command of the vehicle commander.
Expeditionary Team Member	E	An expeditionary team member has the skills necessary to be an effective team member throughout the mission (e.g., leadership/followership, team-care, and self-care).
Operator	O	An operator has the capability to live safely on-board the vehicle and to respond to a warning event to safe a system, operation, or payload using published procedures.[1] This includes but is not limited to emergency response for each vehicle and all habitability duties for each vehicle.
Specialist	S	A specialist has the capability to perform all operator duties and has sufficient knowledge to be capable of responding to a caution event for a system, operations, or payload using published procedures.
Lead[2]	L	A lead has the capability to perform all specialist duties and has sufficient knowledge to be capable of working outside the scope of procedures to meet primary mission objectives and to respond to off-nominal events and unforeseen failures for a system, operations, or payload.
EV	S	An EV specialist crewmember has the capability to perform intravehicular (IV) activities related to EVA hardware and EVA preparation both micro-gravity and surface EVAs. An EV specialist crewmember has the capability to perform all EVA tasks and has sufficient knowledge to respond to off-nominal events during an EVA using published procedures, including performing an incapacitated crew rescue. Additionally, an EV crewmember has the capability to support an EVA lead with real-time coordination of EV crewmembers during an EVA.
EVA	L	An EVA lead has the capability to perform all specialist duties. Additionally, a lead EVA crewmember has the capability to perform real-time coordination of EV crewmembers during an EVA and has sufficient knowledge of EVA operations to work outside the scope of procedures to meet primary mission objectives as well as to respond to off-nominal events and unforeseen failures during an EVA.
Crew Medical Officer	S	A crew medical officer is designated as a specialist and has the capability of responding to medical emergencies using onboard equipment and procedures.
Robotics	S	A robotics specialist has the capability of maneuvering surface robotic devices, maneuvering spacecraft elements and payloads, maneuvering EVA crewmembers, and performing unplanned tasks and has sufficient knowledge of robotics operations to respond off-nominal events to safe the system.

[1] Warning events are more critical than caution events; therefore, it might seem counterintuitive that operators are trained to respond to warning events and specialists to warnings and cautions. However, responding to caution events require a more nuanced understanding of vehicle systems, and specialists are provided the additional training necessary to respond to these events.

[2] The team used the ISS model that commanding to a system (for nominal or off-nominal operations) is assigned to the crewmember responsible for a specific system. However, maintenance and repair for all systems is a separate assigned responsibility. For example, an ECLSS Lead would be responsible for responding to off-nominal events and unforeseen failures by sending commands to the system via a crew interface (such as a laptop or tablet), but the Maintenance Lead would be responsible for performing maintenance and repair of the system.

Table 2. Generic Mars CQRM – Transit Habitat

		Transit Habitat Crew Qualification & Responsibilities							
ROLES (Full Crew)	Vehicle	The first six columns indicate the recommended number of crewmembers and qualifications for each responsibility out of a crew up to six. The last column indicates the number of qualifications for additional crew sizes.							
Mission Commander / Flight Engineer	Transit Habitat	CDR	FE	FE	FE	FE	FE		FE
Expeditionary Team Member	Transit Habitat	E	E	E	E	E	E		E
SYSTEM QUALIFICATION & RESPONSIBILITES									
Piloting Operations									
Piloting (Ascent/Rndz/Entry)	Transit Habitat	-	-	-	-	-	-		-
Complex Operations									
Emergency Operations	Transit Habitat	L (O) (Remain on-orbit)	L(O) (Remain on-orbit)	O	O	O	O		O
Activation/Deactivation	Transit Habitat	S	S	-	-	-	-		-
Logistics (Transfer, Inventory & Stowage)									
Logistics (Transfer, Inventory & Stowage) | One Specialist is Loadmaster	Transit Habitat	S	S	S	S	S	S		S
Vehicle Core Systems (CDH, C&T, ECLSS, EPS, MCS, Propulsion, TCS)									
Command & Data Handling (CDH) w/LAN	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Communication and Tracking (C&T)	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Environmental Control & Life Support System (ECLSS)	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Electrical Power System (EPS)	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Motion Control System (MCS)	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Transit Propulsion System (Prop)	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Thermal Control System (TCS)	Transit Habitat	L(S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Structure & Mechanisms									
Structures & Mechanisms | Incl. Docking System	Transit Habitat	L(S) (MDV/MAV PLT)	L(S) (MDV/MAV PLT)	O	O	-	-		-
Maintenance & Repair									
Intravehicular Maintenance & Repair	Transit Habitat	L (S) (Remain on-orbit)	L(S) (Remain on-orbit)	O	O	-	-		-
Habitability Group									
Habitability (Housekeeping, WHC, Food & Trash Management)	Transit Habitat	S	S	S	S	S	S		S
Photo/TV									
Photo/TV	Transit Habitat	S	S	S	S	S	S		S
Extravehicular Activity (EVA)									
EVA (EVA Operations, EVA Hardware (internal tasks), and EVA Coordination) | micro-G and Surface	Transit Habitat	L = EVA (Remain on-orbit)	L = EVA (Remain on-orbit)	(See Rover for add'l EVA Leads)	(See Rover for add'l EVA Leads)	(See Rover for add'l EVA Leads)	(See Rover for add'l EVA Leads)		-
EV Suit Only | micro-G and Surface	Transit Habitat	-	-	-	-	-	-		-
Integrated Medical Operations									
Crew Medical Officer | Medical Treatment	Transit Habitat	S (Remain on-orbit)	S (Remain on-orbit)	(See Rover for Surface CMO)	(See Rover for Surface CMO)	(See Rover for Surface CMO)	(See Rover for Surface CMO)		Reqm't for 2 per Vehicle
Medical Operations | Exercise Countermeasures, Environmental Sampling (e.g., radiation monitoring, acoustic monitoring)	Transit Habitat	O	O	O	O	O	O		O
Robotics Operations									
Robotics Operations (incl. EVA Robotics (EVR))	Transit Habitat	S (Remain on-orbit)	S (Remain on-orbit)	-	-	-	-		See Rover for Surface ROBO
Track & Capture | Monitor Mars Rndz	Transit Habitat	S (Same as Robotics)	S (Same as Robotics)	-	-	-	-		-
Payloads Group (PLG) | NEW DESIGNATIONS FOR MARS									
Material & Physical Science	Transit Habitat	S	-	-	-	-	-		-
Biological Science	Transit Habitat	S	-	-	-	-	-		-
Botanical Science	Transit Habitat	S	-	-	-	-	-		-
Human Physiology	Transit Habitat	S	-	-	-	-	-		-

The Generic Mars CQRM is designed to be read across each row. For example, for the CDH system on the Transit Habitat, up to four crewmembers would be assigned responsibilities for the system. For a crew of four, there would be two leads (L) and two operators (O). If training constraints prevent the ability to assign two leads, then one or both the leads is assigned as specialist, as indicated by the L(S). For a crew size greater than four, the dash "-" indicates that no additional crewmembers would be trained for responsibilities on this system.

the team determined training hours for each responsibility and level of qualification in the Generic Mars CQRM using quantitative data from current ISS and Earth-to-orbit vehicle training flows, as applicable.

For operator (O) and specialist (S) responsibilities, the team used ISS crew training flow hours documented for formal training in NASA's learning management system. The lead (L) qualifications for vehicle systems are new, Mars-unique qualifications. The team conducted subject matter expert (SME) interviews with training experts from NASA's Flight Operations Directorate (FOD) to determine equivalent training flows for these qualifications. Based on these interviews, the team used flight control backroom training flow hours documented for formal training (noting that the content of a crew training flow would differ from a flight control flow). System lead qualifications for Mars require significantly more flight-assigned training hours training than training for current ISS qualifications.

The Mars EVA lead qualification is a new, Mars-unique qualification. While ISS uses a lead qualification for EVA crewmembers, the Mars EVA lead qualification expands ISS crew responsibilities to include the EVA coordination responsibilities for missions to Mars currently performed for ISS EVAs by the MCC flight control team. EVA lead qualifications for Mars require significantly more flight-assigned training hours than training for current ISS qualifications.

The team used a SME interview to determine training flow hours for the robotics specialist qualification.

3.3 Training Constraints

The Generic Mars CQRM is built to identify the minimum recommended crew qualifications for each area of responsibility necessary for a Mars mission. However, human limitations on skill acquisition and retention need to be considered in modeling a flight-assigned Mars CQRM. To determine these limits for missions to Mars, the team interviewed FOD SMEs and reviewed FOD literature on training retention and training flow duration. Based on ISS operational training limits and SME inputs, the team set a maximum duration of 2 years in the model for a Mars pre-mission, flight-assigned training flow.

The second training constraint that the team considered was the constraint on the allocation of lead qualifications (including piloting, EVA, and system leads) to which a crewmember can be trained to retention, recalling that lead positions provide the expertise within the crew to accomplish primary mission objectives and respond to unforeseen failures without real-time MCC support. The team conducted interviews and working group meetings with FOD SMEs and with a Payload Operations Director to set the following as model constraints on the maximum piloting, EVA, and system lead responsibilities to which a single crewmember can be trained:

- MPCV Pilot + EVA
- Transit Habitat Emer Lead + ECLSS Lead + TCS Lead
- Transit Habitat CDH w/LAN Lead + C&T Lead
- Transit Habitat EPS Lead + MCS Lead + Prop Lead
- Transit Habitat Maintenance & Repair Lead
- MDV/MAV Pilot + Transit Habitat Struc & Mech (Docking) Lead + EVA + Geology Lead
- MDV/MAV Pilot + Transit Habitat Struct & Mech (Docking) + Driving & Navigation Lead
- Rover Emer Lead + ECLSS Lead + (additional CMO training including EVA medical emergency) + EVA + Geology Lead
- Rover Vehicle Core Systems Lead - ECLSS Lead + EVA + Geology Lead
- Rover Struc & Mech Lead + Maint & Repair Lead + EVA + Geology Lead

These allocation constraints mean that once a crewmember is assigned to one set of piloting, EVA, or system lead responsibilities listed above, they would not be assigned additional piloting, EVA, or system lead responsibilities though could be assigned as system, operations, or payload specialists or operators.

3.4 Model Design

The Personnel, Expertise, and Training model is an optimization model with the objective of balancing the training hours across a crew, given a 2-year limitation on flight-assigned training and given an allocation of lead, piloting, and EVA responsibilities. Specifically, the model allocates qualifications to the crew across the entire CQRM, following rules on assignments including:

- Each crewmember is deterministically assigned a fixed allocation of piloting, EVA, and system lead responsibilities.
- Any lead qualifications in the Generic Mars CQRM not assigned to a crewmember are changed to specialist or operator (e.g., if a second lead is not assigned to the Transit Habitat CDH system that qualification is change to specialist).
- All crewmembers are assigned operator or specialist duties for responsibilities levied on all crew as specified in the Generic Mars CQRM (e.g.,

all crewmembers are assigned as specialists for logistics and habitability for the Transit Habitat).

- The remaining operator and specialist responsibilities are randomly assigned to optimize the balance of training hours across the crew (e.g., any crewmember could be assigned as the Transit Habitat CDH specialist).

These rules were built into an optimization model that minimizes the difference between the most training hours and the least training hours among all crewmembers. The model outputs a flight-assigned Mars CQRM showing the CDR, operator, specialist, lead, piloting, and EVA responsibilities assigned to each crewmember and calculates the number of training hours for each crewmember.

A Monte Carlo scheme was established within the Excel® add-on simulation tool Crystal Ball that takes random samples from all possible permutations and combinations of specialist and operator assignments. The Monte Carlo scheme runs generated 500,000 specialist and operator assignments, and the flight-assigned Mars CQRM with the least difference among training hours across the crew was taken as the optimized crew assignment. This optimized crew assignment very well approximates the best balance of training hours among the crewmembers.

The model assumptions and limitations include:

Assumptions:

- Assume Mars architecture of an Orion MPCV Earth-to-orbit vehicle, Transit Habitat, MDV, Rover, MAV with a 30-day short stay on the Martian surface.
- Assume deep space network communication infrastructure that provides for continual but communication delay support from MCC.
- Assume communication that provides for continual communication between Mars surface crew and Mars crew in orbit.
- Assume astronaut candidate training completed prior to Mars flight-assigned training.
- Assume current ISS and Earth-to-orbit vehicle programs of training are valid analogs for Mars flight-assigned training.
- Assume vehicles in the Mars architecture have the information infrastructure and decision-support necessary for the crew to respond to unforeseen failures.

Limitations:

- There are not objective measures of spaceflight training limitations, either in years of training or in the number or groupings of systems, operations, or payloads to which a crewmember can be trained to retention.
- There may be important differences between the analog vehicles used in this report and the vehicles in the final Mars mission architecture. Differences in vehicles may translate to differences in training hours, in training constraints, and in the expertise necessary to respond to unforeseen failures.
- There may be a need for higher levels of expertise on the planetary surface for long-stay missions, including for additional surface infrastructure (such as a Mars Habitat).
- The model balances the training load across the crew but does not balance the in-mission workload.

4. RESULTS AND DISCUSSION

The team led working group meetings with SMEs to determine models to build. Based on these meetings, the team built two flight-assigned Mars CQRM models, a flight-assigned Mars CQRM for a four-person crew with two to the surface and a flight-assigned Mars CQRM with a twelve-person crew with six to the surface. The team led the SMEs through evaluations of these flight-assigned Mars CQRM using the trade space framework to guide the evaluation discussion. These two models provide two examples of a systematic, repeatable process that can be used for evaluating as many other crew sizes (number of crew and expertise) as desired; they are not recommendations on crew size. As stated below, in discussing the results of the twelve-person model, the SMEs agreed that they could not go further in their considerations of the need for vehicle system leads (to drive down crew size to build a third model for analysis) without a better understanding of future vehicles.

4.1 Analysis 1 – Four-Person Crew with Two Crew to Surface

While any size crew can be modeled using this methodology, the first model the team built for analysis was based on a four-person crew with two crewmembers descending to the surface. To build this model, the team conducted SME working group meetings to determine the piloting, EVA, and lead qualifications to assign to the four crewmembers.

NASA currently assigns two pilots to each ascent/entry vehicle to ensure redundancy in critical piloting operations. The working group determined there were two primary options for assigning ascent/entry vehicle pilots for Mars: either two crewmembers would pilot all ascent/entry vehicles or two would pilot the MPCV crew module during operations around Earth or cislunar space and the other two would pilot the MDV and MAV to and from the Martian surface. Based on the recommendation of the astronaut on the working group (who is also a pilot), the team built the model using the 2 x 2 approach: two crewmembers would pilot the MPCV and the other two would pilot the MDV and MAV.

The working group recommended all four crewmembers be EVA qualified to ensure redundancy in pairs of EVA crew for the transit to and from Mars while also ensuring both crewmembers to the surface would be EVA qualified. The working group determined that an MPCV pilot with an EVA lead qualification would be a full allocation of set of responsibilities for a single crewmember.

The working group then discussed the additional responsibilities necessary to assign to the MDV/MAV pilots to meet primary mission objectives. In addition to piloting and EVA responsibilities, these two crewmembers would also need to be assigned as leads for the Transit Habitat docking systems (for docking and undocking the MDV and MAV from the Transit Habitat), as leads for Rover navigation and activation/deactivation, as leads for additional crew medical officer (CMO) training including EVA medical emergency response, and as leads for geology. After creating this list, the working group determined that this would be too many piloting, EVA, and lead qualifications for one crewmember to be assigned. Nonetheless, the team built a model for this crew.

The model output shows that the two MPCV pilots could be trained within the 2-year limitation on pre-mission, flight-assigned training (Figure 1), and the SMEs determined that the allocation of piloting and lead for the MPCV pilots was reasonable. However, the two MDV/MAV pilots would require more than 2 years of pre-mission, flight assigned training.

Table 3 shows an overview of the flight-assigned Mars CQRM modeled for a crew of four based on the working group discussions. In evaluating this flight-assigned Mars CQRM using guidance from the evaluation framework, the SMEs identified the following risks:

- For this modeled four-person crew Mars CQRM, the MDV/MAV pilots exceed the allocation of piloting, lead, EVA assignments for one crewmember, per SME evaluation, and will not likely be able to perform all responsibilities to the level necessary to meet primary mission objectives nor be likely to successfully respond to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect for all assigned responsibilities.

- For this modeled four-person crew Mars CQRM, there are no leads assigned to Transit Habitat systems, meaning the crew will likely not have the capability to respond successfully to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect for Transit Habitat systems.

- For this modeled four-person crew Mars CQRM, there are no leads assigned to the Rover systems, meaning the crew will likely not have the capability to respond successfully to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect for Rover systems.

- For this modeled four-person crew Mars CQRM, there are only two IV crewmembers to support EVA operations. Per the findings of a separate model built by the NESC team, two crewmembers would not be able to adequately manage the workload necessary to provide real-time support to crewmembers performing an EVA on the surface of Mars for technical EVAs operated at the pace of an ISS EVA.

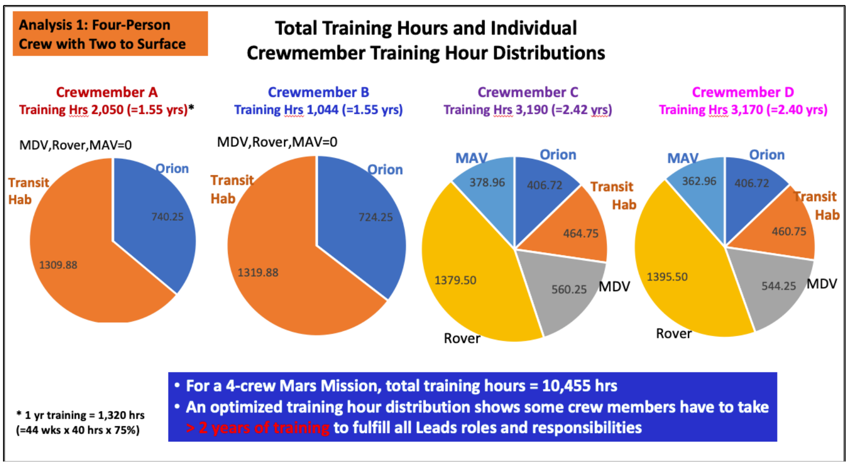

Figure 1. Training Hours for a Four-Person Crew

Table 3. Mars CQRM Overview for Four Crew

Mars CQRM for Four Crew Piloting, EVA, and Lead Responsibilites in Blue	Vehicle	Crewmember A (Orion PLT + EVA Lead)	Crewmember B (Orion PLT + EVA Lead)	Crewmember C (MDV PLT + MAV PLT + Docking Lead + EVA + Geology Lead + Driving & Nav. Lead + Rover Act/Deact. Lead)	Crewmember D (MDV PLT + MAV PLT + Docking Lead + EVA + Geology Lead + Driving & Nav. Lead + Rover Act/Deact. Lead)
CDR	MPCV	CDR	-	-	-
Piloting	MPCV	PLT	PLT	MS	MS
Vehicle Core Systems	MPCV	PLT	PLT	-	-
Emer Response + Habitability + All Other Operations	MPCV	PLT	PLT	MS	MS
CDR	Transit Habitat	-	CDR	-	-
Emer Lead + ECLSS Lead + TCS Lead	Transit Habitat	S	S	O	O
CDH w/LAN Lead + C&T Lead	Transit Habitat	S	S	O	O
EPS Lead + MCG Lead + Prop Lead	Transit Habitat	S	S	O	O
Maintenance & Repair (IVA Tools & Generic Tasks) Lead	Transit Habitat	S	S	O	O
Struc & Mech (Docking) Lead	Transit Habitat	O	O	L	L
Logistics	Transit Habitat	S	S	S	S
Habitability	Transit Habitat	S	S	S	S
Photo/TV	Transit Habitat	S	S	S	S
CMO	Transit Habitat	S	S	O	O
Robotics Ops	Transit Habitat	S	S	-	-
Med. Ops (incl. Exercise Countermeasures)	Transit Habitat	O	O	O	O
EVA Lead | micro-g and Surface	Transit Habitat	EVA	EVA	(See Rover EVA Leads)	(See Rover EVA Leads)
Payloads	Transit Habitat	S	S	-	-
CDR	MDV			CDR	-
Piloting	MDV			PLT	PLT
Vehicle Core Systems	MDV			PLT	PLT
Emer Response + Habitability + All Other Operations	MDV			PLT	PLT
CDR	Rover			-	CDR
Driving & Navigation Lead + Rover Act./Deact. Lead	Rover			L	L
Emer Lead + ECLSS Lead + (additional CMO training incl. EVA medical emergency)	Rover			O +S + L (CMO)	O + S + L (CMO)
Vehicle Core Systems Lead - ECLSS Lead	Rover			S	S
Struc & Mech Lead + Maint. & Repair Lead	Rover			S	S
Logistics	Rover			S	S
Habitability	Rover			S	S
CMO	Rover			(see above)	(see above)
Med. Ops (incl. Exercise Countermeasures)	Rover			O	O
Robotics Ops	Rover			S	S
EVA Lead | micro-g and Surface	Rover			EVA	EVA
Geology Lead (adds to all surface EVA leads)	Rover			L	L
CDR	MAV			CDR	-
Piloting	MAV			PLT	PLT
Vehicle Core Systems	MAV			PLT	PLT
Emer Response + Habitability + All Other Operations	MAV			PLT	PLT

4.2 Analysis 2 – Twelve-Person Crew with Six Crew to Surface

The second model the team built for analysis came about as a result of the discussions in evaluating the first model. In addition to the concerns expressed by SMEs about the training load on the two crew to the surface in the four-person crew model, they also expressed concerns about capability within the four-person crew to respond successfully to unforeseen failures with loss of crew/loss of mission consequences in transit and on the Martian surface. The SMEs did not suggest a specific crew size to model but instead chose to exercise this methodology to address risk mitigation.

With this in mind, the SMEs began discussions on a second model by considering a crew size that allowed for more than two crewmembers to the surface. This model was also built using the 2 x 2 approach for assigning ascent/entry vehicle pilots: two crewmembers would pilot the MPCV during operations around Earth or cislunar space and the other two would pilot the MDV and MAV to and from the Martian surface. The SMEs initially discussed assigning all crewmembers to the surface as EVA leads, although they decided that the MDV/MAV pilots would not need to be geology leads.

In considering the risks to the mission, the SMEs decided on assigning two crewmembers as leads for Rover emergency response (Emer), ECLSS, and for additional CMO training including EVA medical emergency response. Assigning at least four crew to EVA on the surface ensures pairs of EVA crew, and assigning two of these crewmembers as Emer Lead + ECLSS Lead + additional CMO training ensures that one of these crewmembers could always remain inside the vehicle in the event of an emergency on the Rover or a medical emergency during an EVA. The group decided on one lead each for the two additional Rover lead allocations to provide the crew with the capability to respond to unforeseen failures in Rover systems. The team placed these decisions into the CQRM and found this drove the surface crew size to seven.

To reduce this number, the SMEs decided to remove the EVA lead assignment from the MDV/MAV pilots and reassign them to Rover Driving and Navigation Lead + Rover Act./Deact. Lead. The SMEs suggested that a new surface responsibility of EVA specialist be created for suit walk-back on the surface in the event of an off-nominal condition, and the MDV/MAV pilots were assigned to this responsibility. (The training hours for a crewmember to be capable of walking back to their ascent vehicle in an EVA suit is significantly shorter than the training hours necessary to be qualified as an EVA lead.) This decision reduced the surface crew to six.

The SMEs then discussed the Transit Habitat assignments. Recognizing that lead assignments provide capability in the crew to respond to unforeseen failures, the SMEs spent time discussing whether all Transit Habitat vehicle systems would require leads. Points in their discussion included:

- Whether the crew may be able to rely on redundancy to safe future vehicle systems rather than needing leads for all systems.
- Whether systems on future vehicles would need to be managed in the way ISS systems (e.g., EPS) need to be managed, driving the need for leads to respond to unforeseen failures for those systems that do need to be managed.
- Whether different combinations of lead allocations might drive the need for fewer crew.
- How much control the crew will have over future communication networks, or whether the ground would be responsible for these networks.

While the SMEs have knowledge of new Artemis systems under design, there remains significant uncertainty about future systems. Therefore, the SMEs decided on assigning one lead for each of the four sets of allocations for the Transit Habitat core vehicle systems to ensure the capability within the crew to respond to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect.

The team built the model for twelve crew given the SME-discussed assumptions that the two MPCV pilots and four Transit Habitat system leads remained on-orbit, while the other six crewmembers descend to the surface. The model output shows that these twelve crewmembers could be trained within the 2-year limitation on pre-mission, flight-assigned training, and the SMEs determined that the allocation of piloting, EVA, and lead allocations for all twelve crewmembers was reasonable.

In evaluating the flight-assigned Mars CQRM for twelve crew using guidance from the evaluation framework, the SMEs identified the following:

- This is not a recommended crew size and is not a minimum crew size.
- With leads assigned to Transit Habitat systems, the crew will likely have the capability to respond successfully to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect for these systems.
- With leads assigned to the Rover systems, the crew will likely have the capability to respond successfully to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect for these systems.
- There is only one lead for most Transit Habitat and Rover vehicle systems, so there is not redundancy in these responsibilities.
- Most importantly, the SMEs stated that this was a valid and necessary process for determining the capabilities that can be built into a crew of a given size – the capabilities to meet primary mission objectives and to respond to unforeseen failures with potential loss of crew/loss of mission consequences and short time-to-effect.

5. CONCLUSIONS

The Personnel, Expertise, and Training model is designed to quantify to some measure the trade space between the number of crew and the capability within the crew across systems, operations, and payloads in the real-time environment necessary to successfully meet primary mission objectives and to respond to unforeseen failures with loss of crew/loss of mission consequences and short time-to-effect. A flight-assigned Mars CQRM provides a simple layout that shows the capabilities within a given crew that can be used to evaluate the important considerations in the trade space (e.g., operational impact, training workload, and crew resiliency).

The two models presented in this paper demonstrate a methodology for a systematic, repeatable process for evaluating crew size. In discussing the results of the twelve-person model, the SMEs agreed that they could not go further in their considerations of the need for vehicle system leads to drive down crew size to build additional models for analysis) without a better understanding of future vehicles and training programs.

The initial crews to Mars may be deeply involved with the design and development of the vehicles and software they will use on the mission, learning the systems as they are built rather than learning in traditional training flows, giving them a greater understanding of the vehicle, systems, and software to the lead level. Learning the systems as they are built would give them a better understanding of integrated vehicle systems versus a specialized system or subsystem training flow, which will lead to a better understanding of the impacts and consequences of decisions made outside of the known operations and procedures.[3] The need for leads may also be driven by operational considerations including whether the capability of the MAV to provide an escape-to-orbit in the event of an unforeseen failure on the Rover is provided on a mission to Mars.

As NASA makes decisions on mission design parameters including vehicle design, training design, and operational concepts, additional models can be built to support trades in those decisions. If the risks to the mission from a given set of models results and recommended crew size show unacceptable risks, modelers can adjust model parameters and re-run models. The process can be repeated as new technologies are developed and updated mission assumptions are defined.

6. ABBREVIATIONS AND ACRONYMS

C&T	Communication and Tracking
CDH	Command and Data Handling
CDR	Commander
CMO	Crew Medical Officer
CQRM	Crew Qualification and Responsibility Matrix
E	Expeditionary Team Member
ECLSS	Environmental Control and Life Support System
EPS	Electrical Power System
Emer	Emergency
EVA	Extravehicular Activity
FE	Flight Engineer
FOD	Flight Operations Directorate
ISS	International Space Station
IV	Intravehicular
IVA	Intravehicular Activity
L	Lead
LAN	Local Area Network
NASA	National Aeronautics and Space Administration
Maint	Maintenance
MAV	Mars Ascent Vehicle
MCC	Mission Control Center
MCS	Motion Control System
MDV	Mars Descent Vehicle
Med	Medical
MPCV	Multipurpose Crew Vehicle
MS	Mission Specialist
NESC	NASA Engineering and Safety Center
O	Operator
Ops	Operations
PLT	Pilot
Prop	Propulsion
S	Specialist
SME	Subject Matter Expert
Struc	Structures
TCS	Thermal Control System

[3] M. Sonoda. NASA Flight Operations Directorate, Houston, TX. Personal communication (2023).

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