MEDICAL SYSTEM REQUIREMENTS DEVELOPMENT FOR LUNAR OPERATIONS

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ABSTRACT

The major health hazards of spaceflight include exposure to microgravity, higher levels of damaging radiation, extended periods of isolation and confinement, a closed and potentially hostile living environment, and the stress associated with being a long distance from Earth. As we increase the duration of lunar stays with foreseeable communication latencies and disruptions, there will be a progressive need for crew to maintain their own health and independently respond to critical medical events. The Exploration Medical Capability element of the NASA Human Research Program has developed a set of Medical System requirements for lunar orbit and surface operations. These requirements specify the capabilities, processes and procedures of a habitat Medical System needed for the diagnosis and treatment of a range of conditions known to occur during spaceflight. Requirement text is written so as not to constrain innovative design solutions necessary for a resilient system. The requirement set includes attributes and functions the Medical System imposes on additional habitat systems. Although these requirements were specifically developed for lunar surface and orbital operations, they provide a foundation to identify Medical System requirements for other space habitats (e.g., I-Hab, commercial endeavors, etc.).

1 INTRODUCTION

1.1. The Technical Problem: Maintain a Healthy Crew

Although space crews show an amazing resiliency to spaceflight stressors, there are adverse physical and behavioral health effects after several months in low earth orbit (LEO) [1,2]. Upcoming long-duration exploration missions beyond LEO present unprecedented challenges to crew medical care. Gravity transitions, microgravity, lunar gravity, galactic cosmic radiation, lunar dust, confined habitats, separation from family and friends, and high workload to meet mission demands [3] all contribute to human health and performance. Control measures must be taken to provide medical care and prevent adverse health effects in extended space missions outside of Earth's protective envelope.

As missions progress into deep space, communication delays and disruptions will increasingly restrict the crew's reliance on Earth experts [4]. For lunar missions, these round-trip communication delays will range from 5 to 14 sec, and for Mars' missions round trip delays will be up to 40 min. There will also be times of complete communication blackouts. It is pragmatic to assume that life-threatening medical events will occur when advice from Earth experts is unavailable. The crew will be required to act autonomously to emergency medical events. To enable a more autonomous crew will require that medical technology be incorporated into the vehicle architecture. An integrated system will empower the crew to manage their own health care.

1.2. An Integrated Exploration Medical System

The Exploration Medical Capability (ExMC) element of the NASA Human Research Program is using a model-based systems engineering approach (MBSE) to inform medical system needs for lunar missions. MBSE was chosen to help the cross-discipline ExMC team to maintain a common mental model of the integrated system and to foster a handoff of the requirements to the relevant programs [5].

ExMC's Systems Engineering Requirements Development Team (RDT), have generated foundational functional and nonfunctional requirements that specify the needs of a habitat Medical System for lunar orbit and surface operations, addressing its capabilities, processes, and procedures. Foundational functional requirements describe what the architect must address in the system design and the developer must implement. Foundational nonfunctional requirements describe operational and human performance needs on the Medical System operational behavior including attributes such as performance, effectiveness, safety, usability, reliability, security, and extensibility. This paper focuses on Systems Engineering Level 4 Requirements (L4; see Tab. 1) development process and output of the RDT for lunar surface operations.

Table 1. Systems Engineering Requirement Levels

L0	NASA Mission Directorate
L1	NASA Human Research Program
L2	Ground / Space Environments - Habitats
L3	Crew Health and Performance, Structures, …
L4	Medical System, Wellness System, …

2 METHODS

2.1 Requirements Traceability

The RDT catalogued the relationship between each requirement and predecessor products. Requirement traces include parent requirements, medical capabilities, NASA standards for crew health, and requirements written for ISS medical operations. These trace documents are described next.

2.1.1 Surface Operations ConOps and Parent Requirements

Based on discussions with stakeholders, the ExMC systems engineering team developed Concept of Operations (ConOps) for lunar orbit and surface operations that describe the proposed medical system characteristics, behaviors, and performance from an operational perspective [6]. Using the guidance provided in [7, 8, 9] the ConOps establish physical and functional interfaces required for an integrated Medical System. The documents include representative scenarios describing anticipated medical activities. Activity diagrams for the scenarios were created to identify medical system functionality.

2.1.2 Medical Conditions and Capabilities

Leveraging past work [10], the ExMC Clinical and Science Team (CST), composed of physicians, nurses, and other clinically trained experts, have refined a list of high likelihood, high consequence spaceflight medical conditions [11] and the capabilities needed to diagnose and treat these conditions [12]. The list of 120 high priority medical conditions is associated with many required capabilities. The ExMC element has funded the development of the IMPACT model to weigh the pros and cons of each capability [13].

2.1.3 NASA Standard 3001

Every NASA Technical Standard is assigned to a Technical Discipline. The Human Factors and Health Technical Discipline has been assigned two documents, NASA-STD-3001 Vols 1 & 2 [14,15]. Both documents were used for L4 Medical System requirements development.

2.1.4 MORD

NASA Procedural Requirements [16] require spaceflight programs to design and build crew habitats that are consistent with medical requirements written to protect crew health. The International Space Station (ISS) Program imposes the ISS Medical Operations Requirements Document (ISS MORD) [17] on habitat architects. The ISS MORD, signed by NASA, ESA, CSA, Roscosmos, and JAXA, specifies medical operations requirements for ISS and visiting vehicles. This document was used to justify many of the requirements written.

2.2 Conceptual Framework of an Integrated Habitat Medical System

Lengthy discussions among the RDT resulted in a common view of a Medical System's role in lunar surface operations. Fig. 1 presents a framework that assumes operations will occur within a human-rated habitat (i.e., all-encompassing black box). Surface habitats can include a Human Landing System, an exploration extravehicular mobility unit (i.e., spacesuit), or a pressurized rover.

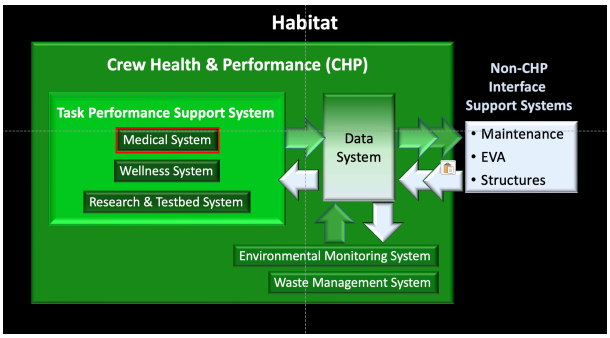

Figure 1. Conceptual framework used to generate Medical System requirements. The Medical System is one part of a broader Crew Health and Performance (CHP) within the space Habitat.

2.3 Medical System

The Medical System, which is the focus of the current effort, is highlighted with a red box in Fig. 1. The Medical System assists crew in preventing, diagnosing, treating, and monitoring medical conditions that can affect crew performance. This includes diagnostic imaging, laboratory analysis and pharmacy management. The knowledge, skills and abilities needed for medical care are handled within this system. The Medical System also provides secured and private consultations between crew and the ground medical support team and the crew's loved ones on Earth. Here the term "medical" refers to the physical, physiological state of the crew while "wellness" refers to support for a healthy lifestyle.

2.3.1 Wellness Support System

The Wellness Support System's (see Fig. 1) role is to promote, maintain and protect the crew's physical and mental well-being. This system provides the health, nutrition, behavioral and sleep management support needed for crew to perform tasks efficiently and with minimal error. The focus is on the provision of countermeasures to prevent, mitigate, or treat adverse physical and behavioral health effects while the Medical System recommends adjustments to these countermeasures to maintain crew health.

2.3.2 Research & Testbed Support System

The Research and Testbed Support System fosters advances in medical science by supporting crew as they conduct research and demonstrations. The knowledge, skills and abilities needed for conducting experiments are handled within this support system.

2.3.3 Task Performance Support System

The Medical, Wellness, and Research & Testbed Systems are viewed as a part of the Task Performance Support System, shown as a light green box in Fig. 1. This system provides operational support to the crew for the execution of activities, including medical activities, as well as maintains Earth-Support situation awareness. Currently, crew receive performance support in the form of procedures, training, scheduling, inventory tracking, and user interfaces. The integrated Task Performance Support system advances these capabilities and integrates them with additional capabilities (i.e., work management, team collaboration, and decision support) needed to support an autonomous crew. The Task Performance Support System will aid in medical data acquisition and interpretation, crew training, medical condition prevention, provide interactive procedures, and track medical inventory. For a detailed description of this system see [18].

The Task Performance Support System is a critical part of Crew Health and Performance (CHP). The large green box labelled Crew Health and Performance (CHP) refers to the definition, planning and initiation of the capabilities needed to maintain crew health and performance [19]. The CHP includes three other critical support systems, the Data, Environmental Monitoring, and Waste Management Systems.

2.3.4 Data Support System

A key property of the Medical System is the provision of medical knowledge that will be collected, stored, updated, analyzed, and secured within the Habitat Data Support System (depicted in the center of Fig. 1). This support system makes those data available to the crew and Earth experts. Data processing includes descriptive and advanced analytics [20]. The consolidation of data within a single system, when appropriate, reduces crew workload and fosters data sharing.

Note the two systems in the bottom right corner that are an inherent part of the greater CHP, the Environmental Monitoring System, and the Waste Management System. These two systems will be described next.

2.3.5 Environmental Monitoring Support System

The Environmental Monitoring Support System ensures that environmental hazards that may affect crew health are monitored, assessed, and mitigated. This includes gravity transitions, radiation exposure, internal thermal atmosphere, odor sources, toxic substances, and harmful acoustics. This system shares these data with the Medical System via the Data System to help identify issues before they affect crew health.

2.3.6 Waste Management Support System

The Waste Management Support System provides containment and disposal solutions for managing biohazard waste. Biohazardous waste products include contaminated personal protective equipment, IV tubing, suction canisters, cultures, etc.

The rightmost box in Fig. 1 represents three additional non-CHP habitat systems needed to support the Medical System.

2.3.7 Maintenance Support System

The Maintenance (and repair) Support System's role is to support crew habitat upkeep. Maintenance and repair have consumed a great deal of ISS crew time and have significantly increased crew workload. This system ensures that medical equipment is performing as expected.

2.3.8 EVA Support System

The EVA Support System provides the required capabilities for crew health and performance during lunar orbit and surface activities.

2.3.9 Structures Support System

The Structures Support System provides the volume, power, tethers, etc. needed to perform medical operations. This system also provides technologies and procedures to aid in the development and manufacturing of new materials on lunar and Mars surfaces.

3 RESULTS

Just over 400 requirements for a lunar orbit and surface operations Medical System were generated by the RDT. Eighty-three of these are functional and 37 are non-functional Medical System requirements. The requirement set generated also includes attributes and functions the Medical System imposes on the ten additional habitat systems shown in Fig. 1. These requirements are jointly referred to as *interface requirements*.

Each recommended requirement and the affiliated rationale and traces have been reviewed and approved by NASA management, systems engineers, and clinicians. Each requirement set is housed in a Cradle database. The ConOps, Medical System and interface requirements with rationales, and associated clinical capabilities, human health standards, and ISS medical

requirements were input into a SysML model utilizing MagicDraw.

4 DISCUSSION

Apollo missions showed it was safe to spend a few days on the lunar surface [21]. As we increase the duration of lunar stays with foreseeable communication latencies and disruptions, there will be a progressive need for crew to maintain their own health and independently respond to critical medical events. This need has been identified as a red risk by the NASA Human Research Program [4].

The ExMC element has developed a set of Medical System requirements for lunar orbit and surface operations. Requirement text is written so as not to constrain innovative design solutions necessary for a resilient system [22]. These requirements provide a common view that specifies the capabilities, processes and procedures needed for the diagnosis and treatment of a range of conditions known to occur during spaceflight. The requirement set also includes attributes and functions the Medical System imposes on other habitat systems. They describe all inputs, outputs, and required relationships between the inputs and outputs for all stakeholders and the technical community. These requirements provide a foundation to identify Medical System requirements for other space habitats (e.g., I-Hab, commercial endeavors, etc.).

9. REFERENCES

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