Assessment of Crew Time for Maintenance and Repair Activities for Lunar Surface Missions

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Abstract— **NASA is currently evaluating different methods to predict how much time crewmembers will spend conducting repair and maintenance activities on future space missions. As mission scope and spacecraft architectures change, understanding how crew repair and maintenance timelines are impacted by mission operations and technology changes is vital for future mission planning. Past work has been done using historical InternationalSpace Station (ISS) data to accurately predict crew habitation and operation timelines, resulting in the development of NASA's Exploration Crew Time Model (ECTM). However, understanding crew maintenance and repair requirements has posed a unique challenge due to the complexity of available datasets, the probabilistic nature of sub-system failures, and theimpacts of reliability growth on failure rates. This paper presents a methodology to collect and condition empirical repairand maintenance time data from available data sets, to extrapolate from that data to estimate projected maintenance and repair times for a lunar Surface Habitat (SH), and to assess how uncertainty in repair time could impact utilization time onthe lunar surface. NASA ISS maintenance and crew time data are logged into two central databases: the Maintenance Data Collection (MDC) and the Operations Planning Timeline Integration System (OPTimIS). Separately, each of these two datasets capture only portions of the complete set of data required to generate an accurate assessment of crew time spenton maintenance activities at a sub-system level. To create a more useful crew time estimate for maintenance timelines, the authors developed a methodology to capture relevant data fromeach set and combine and utilize that data by linking crew time requirements to specific components. The authors compare the failure logs in the MDC to crew activity logs pulled from OPTimIS and then process the data to estimate required repairtimes for each failure and repair event. The entire maintenanceactivity dataset is then categorized based on the class of failed component to ensure a significant sample size for each class and accurate crew time estimates for any components lacking relevant data. This resultant component repair time data can beused in the future to generate Mean Time to Repair (MTTR) estimates and confidence intervals for each class of component based on a probabilistic distribution of documented maintenance events. These improved MTTR values can then be applied to candidate element sub-system architectures, along with component Mean Time Between Failure (MTBF) data to generate distributions for potential required system crew repairtime estimates for a given mission. The authors applied these modeling methods to a case study of a crewed mission to the planned SH and produced expected corrective maintenance crew time distributions. The results produced an expected corrective maintenance crew time at over 24 hours per mission, and a maintenance crew time distribution that reflects the importance of planning for sufficient maintenance requirements each mission. Repair time distributions can then be used to develop more accurate crew schedules and to assess potential available utilization time.**

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I. INTRODUCTION

As NASA's current human spaceflight plans mature, there is a need for a more robust analysis of crew time requirements to determine available time for crew utilization and science and to ensure that mission goals and objectives are being met. In the past, analysis has been completed using historical International Space Station (ISS) crew time data to assess thecrew time demands of human exploration missions [1]. Theseresults were then utilized to predict crew time availability forother human exploration missions by linking parametric time liens to mission parameters. The effort described in this paper builds upon these previous modelling efforts, taking a more focused look at the probabilistic crew time required for crewmaintenance and repair activities and generating empiricallybased estimates for repair time at a component level. This data can be used to estimate total required repair time distributions for future missions. Maintenance and repair activities can be a driver for crew time, especially as system complexity increases.

Historical ISS data can be reasonably extrapolated to develop estimates for the time required to complete scheduled crew tasks, such as crew sleep, exercise, and preventative maintenance on future missions. However, extrapolating time requirements for repair tasks is more complex and mustbe handled differently than other crew time items. Repair tasks are unique in that they are probabilistic in nature, driven by random failures. To accurately predict crew time requirements for repair tasks, historical repair time data wasused to assess crew time requirements for future missions.

To accomplish this, historical ISS crew repair times were collected and organized based on the type of failure and the type of component. Historical failures are sorted into specific component categories and then used to develop statistical distributions of projected repair time for each component type. This data is then used, along with the system design for future spacecraft and projected component failure rates, to assess total potential required repair times for future missions.

By combining crew time estimates for more deterministic tasks from the Exploration Crew Time Model (ECTM) [2] and the probabilistic maintenance crew time analysis results developed in this effort, it is possible to develop more accurate and comprehensive crew time schedules for future exploration missions. This, in turn, allows for an evaluation of the time available for exploration utilization and the potential to meet mission goals and objectives.
This paper will first detail the previous efforts and models created to establish crew timelines and the limits of these models. A detailed introduction into the sources of historical ISS data used for analysis is provided, followed by an overview of the methodology used and an explanation of how the data is collected. The data conditioning process is then outlined to explain how the two parameters required for modeling, the MTTR and a component's repair ratio, are calculated. The paper also describes the maintenance and crew time model [2], which utilizes failure rates and expected repair times to generate expected repair timelines over a given mission duration. Finally, a case study is presented to demonstrate how the generated component-level maintenance and repair time data can be used to develop estimates for potential total repair time for a candidate mission. The candidate mission for this study is a 28-day. 2 crew mission in the lunar Surface Habitat (SH). The SH is a proposed lunar surface element with life support systems capable of inhabiting crew members on the lunar surface for an extended duration and is currently planned on being delivered and inhabited by NASA crew members as early as 2029. Because of the proximity to the SH's planned delivery deadline to the lunar surface, the SH was deemed the best first case to conduct further analysis of expected maintenance requirements. The result of this case study is a cumulative distribution function of the required crew time for repairs.

II. BACKGROUND

When planning for future human spaceflight missions, historical data regarding how crew members spend their time is an invaluable source. ISS crew time data in particular is extremely informative, as the ISS has been continuouslyoccupied for over 20 years. ISS crew time data has been logged and documented using NASA's Operational Planning Timeline Integration System (OPTimIS) [4].

OPTimIS contains a complete daily log of crew activities on ISS, with crew and ground control teams recording descriptions and durations of all activities daily. Although crew time activity is continuously logged in OPTimIS, detailed crew time analysis using the database can be difficult. While tasks are categorized at a high level, detailed descriptions of individual tasks within OPTimIS are captured as text strings that are manually inputted. There is no structured format or language consistency for these text strings, making it difficult to perform detailed statistical analysis for specific crew time activities. In 2017, researchersat the NASA Langley Research Center and Binera, Inc. begandevelopment of a data conditioning tool to allow for more discrete categorization and analysis of the semi-structured data from OPTimIS. The data conditioning tool processes rawOPTimIS text data through a set of nested text libraries that filter the text into activity categories and subcategories (see Fig. 1).

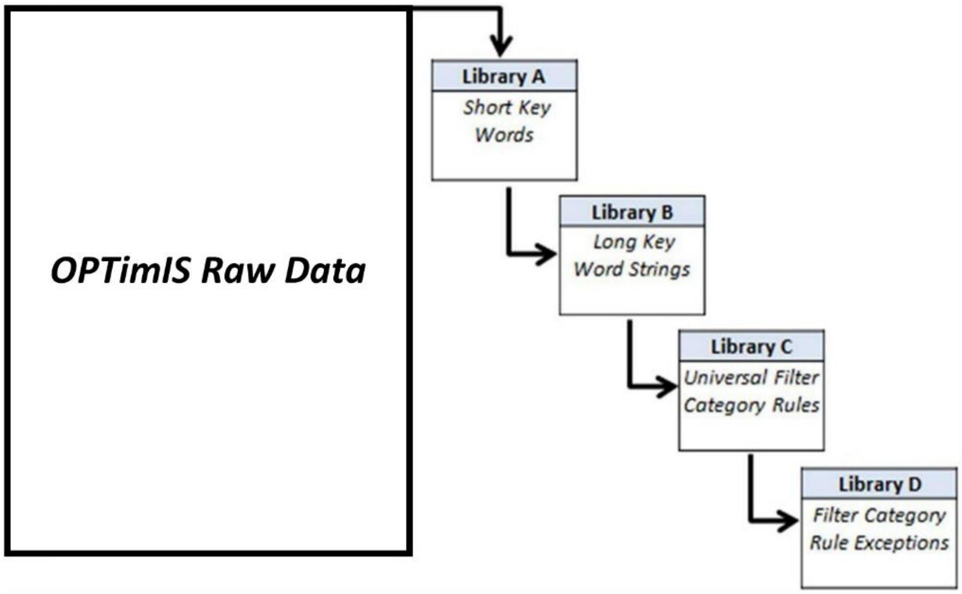

Figure 1. ECTM Categorization Library Process

The data conditioning tool has the ability to categorize all crew time tasks into designated crew time activity categories and subcategories. For maintenance and repair time tasks, categorization is performed down to the component and failure type level. Categorizations can be flexible, allowing for tasks to be grouped by different types of parameters. Using the categorized data, analysts can assess average times and distributions required to complete different tasks and the frequency of occurrence of these tasks over time.

However, because repair activities are driven by random failures the crew time spent on maintenance cannot be analyzed deterministically at the mission level with the standard allocation methods. Rather, repair times must be evaluated at the component level and then combined with sub-system design data and failure rate data to project required repair times for future missions. Unlike for other tasks, where average crew time requirements can generally be defined, repair time requirements will take the form of a probability distribution, representing the inherent uncertainty in failure occurrence.

III. REPAIR CREW TIME DATA CONDITIONING

Crew repair time data is extracted from the Maintenance Data Collection (MDC) database and from OPTimIS via a data tool. To get a complete picture of the maintenance activities, different information is pulled from both sources. MDC provides a complete list of the required maintenance actions, and information such as part name and number, failure and maintenance dates, corrective or scheduled maintenance, and repair category are all collected [3]. OPTimIS details the day-to-day crew activity on board the station chronologically and provides insight into how and when the maintenance requirements are completed. From OPTimIS, the total duration of maintenance events, amount of crew members involved, and the total crew time spent on maintenance events are collected.

The two data sets contain some data overlap, but the shared data between them is often inconsistent. For example, MDC also contains time logs for the duration of the listed maintenance event, but it often lacks preparation and post-work activities that are included in OPTimIS. However, if the specific maintenance event is grouped with another event in OPTimIS, or if the task description is vague, the time duration logged in MDC can be considered. Similarly, if MDC fails to properly log pertinent component information, the OPTimIS description may provide details on the component and its performed maintenance. Corroborating the data between MDC and OPTimIS also has the advantage of verifying the maintenance data logged in each source. MDC and OPTimIS data logs are inconsistent in the format and syntax in which they are entered, which prevents the direct extraction of information from each source. Using both data sets to extract data provides the most complete and accurate description of maintenance activities onboard ISS.

Prior to analysis, the collected repair data is divided into multiple subsets. First, the data is organized based on the type of component maintenance is required on. Inherently, not all components onboard the ISS have sufficient maintenance history, some components may have never failed, or there may only be one or two data points for a specific part. Also, specific components can differ between system architectures. Because of these two factors, relying on specific component maintenance data will not suffice when attempting to accurately predict maintenance time for future missions. Therefore, components are grouped into 16 categories, shown in Table 1 below. The components were categorized into these 16 categories based on common functionality and repair requirements. Grouping components into these 16 categories provides more data for each component type and maintenance data components without the need for additional failure history. Additionally, by splitting the crew time requirements into component categories, this methodology is adaptable for any future mission or system architecture as technologies change and evolve.

Table 1. Component Category List

1.	Air Valve
2.	Liquid Valve
3.	Air Component
4.	Liquid Component
5.	Complex Air Assembly
6.	Complex Liquid Assembly
7.	Electronics
8.	Pump
9.	Sensor
10.	Tank
11.	Fan
12.	Filters
13.	Reactor Assembly
14.	Heat Exchanger
15.	Plumbing
16.	EVA

The component maintenance data is then categorized by the type of repair event that occurred: Repair and Replace (R&R) or other (non-R&R). The non-R&R events are comprised of troubleshooting events, inspections or services, cleaning, or any other maintenance or repair conducted on a component that does not involve the component being replaced. All R&R maintenance activities involve a component requiring replacement.

The data is separated into these two repair event subcategories to analyze the rate of maintenance events a component needs prior to being replaced. For most components on the ISS, a Mean Time Between Failures (MTBF) has already been assessed and documented. The MTBF is a value that describes the probability distribution of a component's failure rate and is used in the probabilistic analysis conducted on corrective R&R events. However, relying only on the MTBF to predict a component's rate of maintenance events will exclude the non-R&R maintenance data and produce an inaccurate rate of all maintenance events. To produce a probability distribution of non-R&R events, a ratio of non- R&R to R&R events is needed to adjust the MTBF to a rate that defines the frequency of all maintenance and repair events, not just failures. In addition to the need to track the rate of non-R&R events to R&R events, the crew time spent on the two activity types tend to differ significantly. A more precise average crew time spent on repair, or mean time to repair (MTTR), can be derived based on the two activity types if separated.

The repair data is then divided into corrective and scheduled maintenance events. For the scheduled maintenance events, a rate of repair events will be derived for each component either from average time between repairs and/or a historical nominal repair schedule. The average times spent on scheduled repairs and rate of scheduled repairs are used to produce an estimated time on scheduled repairs for each component over the defined mission duration. The corrective maintenance events are processed through the probabilistic Maintenance and Repair Model to produce probability distributions of individual component failures and repairs over the defined mission duration.

IV. DATA ANALYSIS

A. Scheduled Maintenance

Scheduled maintenance events are analyzed outside of the probabilistic analysis of the corrective maintenance events. Also, because scheduled maintenance is specific to individual components and not random, the time and frequency of repair data was not spread to components through categories. Rather, only components with known or observed scheduled maintenance were analyzed in this analysis. Once the scheduled maintenance data is organized and collected, the average time to repair and time between repairs is calculated. Because not all systems onboard the proposed SH are operating at 365 days a year, component repair frequencies are adjusted from the ISS operating durations to match the predicted SH operating durations. Once the repair frequencies are adjusted, any repairs that occur more frequently than every two missions are assumed to occur every mission. Repairs that occur less frequently than every two missions have their repair times allocated across each mission. For example, an average repair time of one hour per every three missions is allocated as one-third of an hour each mission. The total scheduled maintenance time of the SH is the sum of all the system schedule maintenance crew times.

B. Corrective Maintenance

Once the corrective maintenance events are organized properly, the MTTR and repair ratios are needed from the data to input into the Maintenance and Repair Model. For the MTTR, times for R&R events and non-R&R events are calculated separately. When analyzing the crew time data on repairs, manual data manipulation is conducted to ensure accuracy of the results. For example, some maintenance events may involve increased preparation work due to situational or location circumstances. Often these examples skew the results to the point that they no longer accurately reflect the crew time spent on repairing the other components in the category. These examples can either be omitted completely from the data analysis or, if the component has a large set of maintenance data that is consistent within itself, the component data can be separated from the category and analyzed individually. For example, if an air valve component, Air Valve X, requires complex rack reconfigurations along with procedure reviews that the other air valve components do not require, the MTTR for Air Valve X will not influence the MTTR of the air valve category. In the model, Air Valve X will use its own component specific MTTR while the other air valve components use the air valve component category MTTR. Additionally, if a single component contains a significant amount of maintenance data it can also be analyzed individually regardless of the comparability between its time data and the rest of the component's category data. For this analysis, any component that contained 8 or more separate maintenance events of the same maintenance type on the ISS since 2012 was eligible to be analyzed in the model using the specific component data instead of the component category data.

With the data properly separated, the MTTR is calculated by taking the average crew time of all the selected maintenance activities. The repair ratio is calculated simply as a ratio of the amount of non-R&R events to R&R events. The repair ratio calculated is used in the Maintenance and Repair Model as a parameter that provides a more accurate prediction of frequency of repairs compared to using known failure rates associated with components. Similar to the MTTR analysis, the repair ratio for some components can be analyzed outside of the component category for increased accuracy.

C. Modeling

The resulting MTTR and repair ratios are assigned to their respective components and are fed into the probabilistic Maintenance and Repair Model. This model incorporates the MTTR, repair ratio, and other component data and calculates the maintenance crew time distribution, using the approach described by Owens [2]. Additional data outside the MTTR and repair ratios used to model expected failure probabilities include component failure rates, operating hours, and duty cycles. The model predicts expected component failures based on component failure rate, which is defined as a failure per operating hour rate. To predict failures using the failure rates, the operating hours for each component must be defined in the model. Because the crewed SH missions will occur each year, the operating hours defined in the model are hours per year to incorporate the total yearly crewed operating hours and uncrewed operating hours. The component's duty cycle represents the time the component is function as a ratio of the total time. For example, a component that operates at 20 minutes per hour would hold a duty cycle of 0.33. The duty cycle helps better define the operating hours of components in complex systems, such as water recovery, that operate during the crewed portion of the year and operate at different rates. For each item, the distribution of the number of R&R events is calculated based on the failure rate estimate, and the distribution of the number of non-R&R maintenance events is generated based on the number of R&R events and the repair ratio. These distributions are multiplied by the respective MTTR values, and the results are added together (i.e., convolved) to generate the distribution of total maintenance crew time. The Cumulative Distribution Function (CDF) of the resulting distribution indicates the Probability of Sufficiency (POS) associated with a given level of crew time [2].

The total maintenance crew time distribution can be completed by including the total scheduled maintenance times over the mission. Because analysis is conducted down to the component level, changes in system architecture will alter the overall crew time distribution. This level of analysis provides insight on varying crew time requirements for different subsystem and system architectures, allowing for the results of this analysis to be used in predicting crew time of future missions by analyzing multiple system architectures. Through the combination of both the non-probabilistic and probabilistic activities a more accurate, data-driven crew time schedule can be created.

V. SURFACE HABITAT CASE STUDY

Following data collection and conditioning, the Maintenance and Repair Model is used to generate expected corrective maintenance time and expected corrective maintenance time distributions. Component repair and maintenance time data, generated using the data analysis process, is input into the model to develop an integrated maintenance time estimate for a candidate lunar surface mission. The candidate mission is a 28-day day crewed mission on the lunar surface with the crew living and operating out of a fixed lunar SH. The repair timeline was generated from the sum of the repair time probability distributions of each component on the SH. To model the SH, a complete list of components onboard the SH first had to be collected and organized. Each SH component was allocated to one of the 16 component categories described in the Methodology section, using the same criteria as the ISS component categorization. Each component in the SH was assigned a MTTR and a repair ratio based on the component or component type. The MTTR and repair ratios calculated for each component category using the ISS data are attached to the respected SH component of each category. However, SH components with sufficient historical ISS maintenance data are assigned the MTTR and repair ratios calculated from its specific component data, not the component category data. This prevents any unnecessary categorization that leads to inaccurate component maintenance times.

A. SH Architecture

After determining crew time distributions for each component or component category on the ISS, POS crew times for repair on the SH were derived. The team aligned the crew time distributions to the different components in the SH sub-system architecture. The baseline case for this study includes 17 different SH subsystems, listed in Table 2 below.

Table 2. List of SH Systems and Subsystems Analyzed in the SH Case Study for Corrective Maintenance

1.	Urine Processing (UPA)
2.	Water Processing (WPA)
3.	Brine Processing
4.	Pressure Control & Relief (PC&R)
5.	Air Circulation
6.	Air Temp. and Humidity Control (ATHC)
7.	Atmospheric Constituent Monitoring (ACM)
8.	Trace Contaminant Removal (TCCR)
9.	Oxygen Generation (OGA)
10.	High Pressure Oxygen Compressor (HPO_2)
11.	CO2 Removal
12.	CO2 Recovery
13.	Waste Management System (WMS)
14.	Electric and Power System (EPS)
15.	Communications and Tracking (C&T)
16.	Command & Data Handling (C&DH)
17.	Active Thermal Control (ATCS)

For the model analysis, a maintenance component list was created listing the components included in system with their quantity and category. The Maintenance and Crew Time Model must also account for the usage of each component and the component's duty cycle. For this study, the EPS, C&T, and C&DH systems were analyzed as running 365 days a year and all other systems running 28 days a year.

Because three systems are operating while the crew is not occupying the SH and cannot conduct maintenance, the failures that occur during this time should be analyzed separately. The model runs separate probabilistic analyses for the two different corrective maintenance time based on SH occupancy: crewed and uncrewed maintenance. The crew maintenance describes the corrective maintenance activities that occur following a failure while the crew is habiting the SH, and uncrewed corrective maintenance describes the maintenance the crew must complete to resolve failures that occurred while the SH was unoccupied. Differentiating between the two categories is necessary for future mission planning, as the uncrewed maintenance will likely require being completing upon SH activation or shortly after.

B. Results

The POS crew time for corrective maintenance per crewed mission is shown in Fig. 2. The POS distributions for the uncrewed corrective maintenance, crewed corrective maintenance, and total corrective maintenance are displayed. The dashed gray vertical lines in Figure 2 represent the expected maintenance times at POS values of 50%, 80%, 90%, 95%, and 99%. The POS percentages are labeled next to each of their respected data lines. The thick-dashed black line represents the expected required corrective maintenance time for the SH. The expected value is the cumulative sum of the required corrective maintenance time calculated by the model permission.

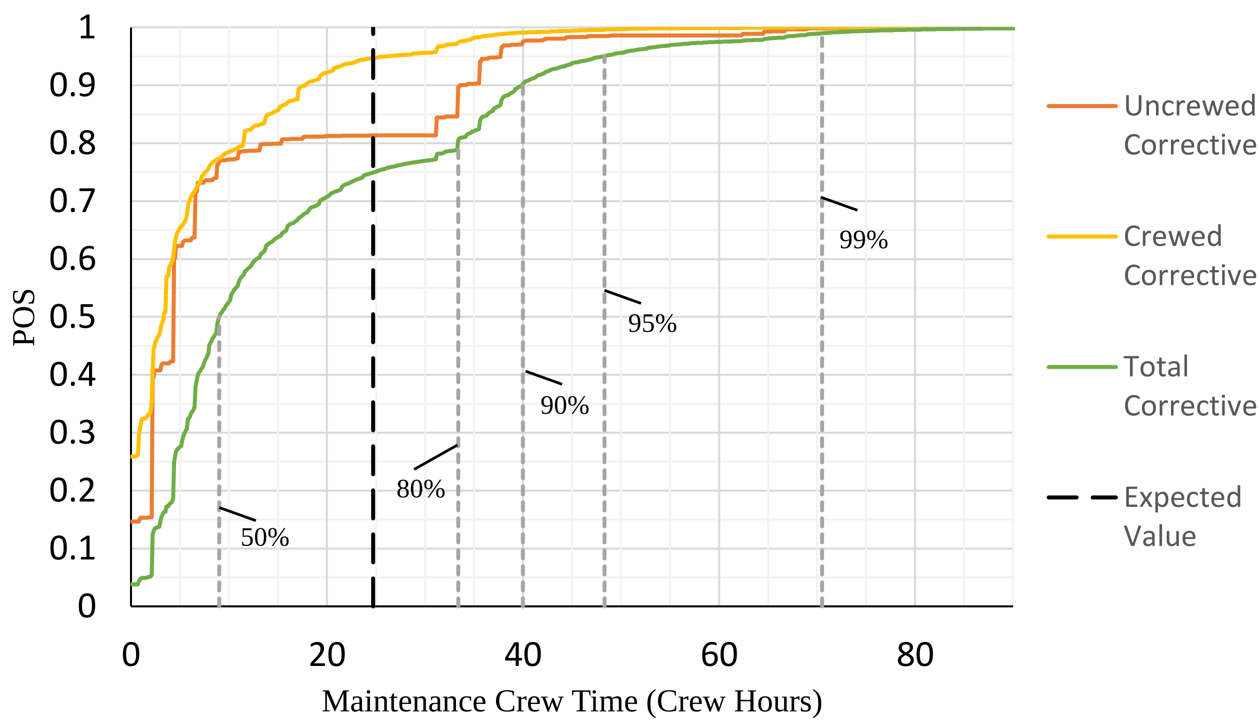

Figure 2. POS Corrective Maintenance Crew Time Per Mission

Table 3 below shows the expected crew time results of the selected POS graphically represented in Figure 2.

Table 3. Select POS for Distribution Analysis of SH Systems and Corresponding Required Repair Time

POS	Required Repair Time (hours)
50th	9.0
Expected Value	*24.7*
80th	33.4
90th	40.0
95th	48.3
99th	70.5

The results show a significant increase between the bottom 50% POS of 9 hours and the 99% POS value of over 70 hours. To plan for a 99% POS corrective maintenance crew time, a large amount of crew time would have to be available for maintenance and repair activities. The additional expected maintenance crew time from planning for a higher POS may come directly out of the expected utilization time. If this were to occur, it would likely limit the crew time available for utilization activities.

The expected maintenance crew time can also be grouped by SH system, showing where the crew are expected to spend most time on maintenance. Comparing the systems and their maintenance times provide insight into what causes increased maintenance times for future mission planning. Additionally, the expected maintenance time results can be group by component category, identifying the components that are the highest drivers in maintenance time. Fig. 3 below displays the total, crewed and uncrewed combined, expected corrective maintenance times grouped by SH system, with the Environment Control and Life Support System (ECLSS) subsystems – UPA, WPA, Brine Processing, PC&R, Air Circulation, ATHC, ACM, TCCR, OGA, HPO2, CO2 Removal, CO2 Recovery, and WMS - grouped as a whole.

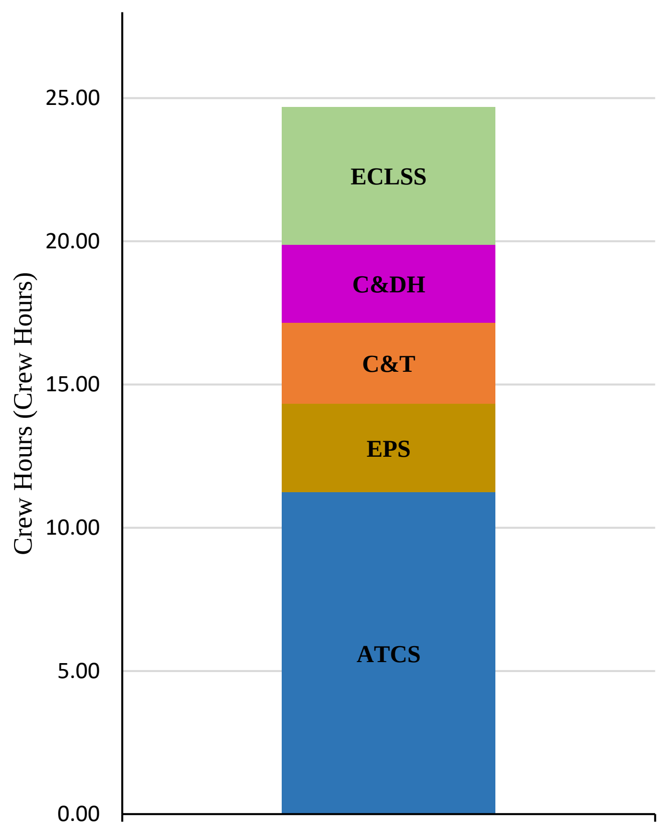

Figure 3. Total Expected Corrective Maintenance Time for SH Systems per Mission

As anticipated, the systems running 365 days a year are expected to experience an increased amount of component failures during the uncrewed duration increasing the corrective maintenance time requirements. Additionally, systems that are planned to contain external maintenance components will require additional crew time for maintenance due to Extravehicular Activity (EVA) requirements. For this analysis all EVA preparation and EVA post-work requirements are included in the expected crew time per repair, resulting in significant increases in crew time requirements compared to Intravehicular Activity (IVA) maintenance. Because of the effects of increased operating times and EVA needs, the thermal system (ATCS) is the largest driver of expected corrective maintenance crew time. This is followed by the power, communications, and data systems, which all operate at 365 days a year.

Table 4 details the expected corrective maintenance times for each component category, based on the total amount of components the category contains on the SH.

Table 4. Component Categories of Expected SH Components and the Total Expected Corrective Maintenance Time for each Category

Component	Total Expected Corrective Maintenance (hour)
Plumbing	2.21 E-03
Tank	0.01
Filter	0.06
Sensor	0.07
Air Component	0.10
Fan	0.11
Liquid Valve	0.17
Liquid Component	0.22
Reactor Assembly	0.41
Pump	0.44
Heat Exchanger	0.51
Complex Liquid Assembly	0.64
Air Valve	0.81
Complex Air Assembly	2.2
Electronics	6.43
EVA	12.52
TOTAL	**24.70**

As shown previously, the largest driver in expected SH maintenance time is based on EVA needs for maintenance and component over the course of the year, not just during the mission duration. Components utilizing fewer moving parts, such as the plumbing, tanks, filters, and sensors, all see the lower amount of expected corrective maintenance. Another driving factor in expected corrective maintenance time on specific components is the quantity of each component category in the SH. Air valves are simple mechanisms, but the quantity of the component along with the high expected operation time of the air valves increases the expected time for corrective maintenance.

VI. CONCLUSION AND FUTURE WORK

The methodology presented here provides a framework to combine empirical data from ISS operations with validated maintenance models to generate maintenance and repair crew time estimates for future exploration missions and inform mission crew time requirements. The results presented demonstrate the importance of creating a crew time schedule and the impact of maintenance and repair time.

The ISS represents the best source of data for understanding maintenance and repair activities for long-duration missions. While there are current logs of maintenance times onboard the ISS, in OPTimIS and MDC, using both sources to organize data for analysis provides the most complete picture of crew time spent on maintenance. Post data collection, the probabilistic analysis of maintenance times as a function of rate of repairs and average repair times produces the most accurate projections of maintenance crew time of future missions. Analyzing at the component level allows precise maintenance crew time projections across multiple system architectures for planning of future missions. As the study continues, additional adjustment on crew times will be made to project missions with different communication times, gravity environments, and new system technology.

As lunar/mars and beyond architecture matures, there will be an improved understanding of how mission and system architecture affects both non probabilistic and probabilistic crew time data. This new understanding can be used to update our assumptions, further refining our ability to produce accurate crew time schedules and refine the repair time distribution.

APPENDIX

A. NOMENCLATURE

1. ACM = Atmospheric Constituent Monitoring
2. ALGS = Airlock Gas Recovery System
3. ATCS = Active Thermal Control System
4. ATHC = Air Temperature and Humidity Control
5. C&DH = Command and Data Handling System
6. C&T = Communication and Tracking System
7. ECLSS = Environmental Control and Life Support System
8. ECTM = Exploration Crew Time Model
9. EPS = Electrical Power System
10. EVA = Extravehicular Activity
11. FD&S = Fire Detection and Suppression System
12. HPO_2 = High Pressure Oxygen Compressor System
13. ISS = International Space Station
14. MADS = (ISS) Maintenance Data Collection
15. MDC = (ISS) Maintenance Analysis Data Set

16. MTBF = Mean Time Between Failure
17. MTBR = Mean Time Between Repairs
18. MTTR = Meant Time to Repair
19. OGA = Oxygen Generation Assembly
20. OPTimIS = Operational Planning Timeline Integration System
21. ORU = Orbital Replacement Unit
22. POS = Probability of Sufficiency/Sufficient
23. PC&R = Pressure Control and Relief
24. SH = Surface Habitat
25. TCCR = Trace Contaminant Removal System
26. UPA = Urine Processing Assembly
27. WMS = Waste Management System
28. WPA = Water Processing Assembly

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BIOGRAPHY

Chel Stromgren *currently serves as the Chief Scientist of Binera, Inc. Risk Analytics Division. In this role, Mr. Stromgren leads the development of probability and risk-based strategic models and strategic analysis of complex system development. Mr. Stromgren has supported NASA in the analysis of Space Shuttle and International Space Station operations in the post-Columbia environment and has led the development of strategic campaign models for the lunar exploration initiatives. He holds a Bachelor of Science degree in Marine Engineering and Naval Architecture from the Webb Institute and a Master of Science degree in Systems Management from the Massachusetts Institute of Technology.*

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William Cirillo *currently serves as a Senior Researcher at NASA Langley Research Center in Hampton, Virginia, where he has worked for the past 20 years in Human Space Flight Systems Analysis. This has included studies of Space Shuttle, International Space Station, and Human Exploration beyond low Earth orbit. In 2005, Mr. Cirillo served at NASA Headquarters as a core member of the Exploration Systems Architecture Study where he was responsible for studying the use of Ares I/Orion in meeting future ISS crew and logistics transportation needs. Mr. Cirillo currently leads a team of analysts in assessing the manifesting of assembly and logistics flights human exploration beyond low Earth orbit at a strategic and tactical level.*

Andrew Owens *is an Aerospace Engineer in the Space Mission Analysis Branch (SMAB) at NASA Langley Research Center in Hampton, VA. His work focuses on supportability, reliability, test planning, logistics, and risk assessment for human spaceflight, and on integrated systems analysis, optimization, and tradespace exploration to inform system and mission design. Dr. Owens received a BS in Mechanical Engineering (2012) from Rice University, as well as an SM in Aeronautics and Astronautics (2014) and a PhD in Space Systems (2019) from MIT.*