Assessment of Crew Time for Maintenance and Repairs 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, it will be necessary to understand how crew repair and maintenance timelines are impacted by mission operations and technology changes. Past work has been done using historical 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 the impacts of reliability growth on failure rates. This paper presents a methodology to collect and condition empirical repair and maintenance time data from available data sets, to extrapolate from that data to estimate projected maintenance and repair times for a lunar Surface Habitat, and to assess how uncertainty in repair time could impact utilization time on the lunar surface.**

NASA International Space Station (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) respectively. Separately, each of these two datasets capture only portions of the complete set of data required to generate an accurate assessment of crew time spent on maintenance activities at a sub-system level. MDC provides a detailed catalog of failure events and an overview of the failure's required maintenance and OPTimIS provides a description of crew activities and crew time durations dedicated to maintenance. To create a more useful crew time estimate for maintenance timelines, the authors developed a methodology to capture relevant data from each 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 repair times for each failure event. Data is also classified by the outcome of each repair event, whether the failed component was replaced or whether it was repaired in place. The entire maintenance activity dataset is then categorized based on the class of failed component to allow for a statistically significant sample size for each class and to provide accurate crew time estimates for any components lacking relevant data.

This resultant component repair time data can be used 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 repair time estimates for a given 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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1. 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 the crew time demands of human exploration missions [1]. These results were then utilized to predict crew time availability for other 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 crew maintenance and repair activities and generating empirically-based 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 it takes 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 must be 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 was used 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) 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 Mean Time to Repair and a component's repair ratio, are calculated. The paper also describes the Maintenance and Crew Time Model, 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 result of this case study is a cumulative distribution function of the required crew time for repairs.

2. 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, with the ISS having been continuously occupied for over 20 years. ISS crew time data has been logged and documented using NASA's Operational Planning Timeline Integration System (OPTimIS).

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, researchers at the NASA Langley Research Center and Binera, Inc. began development 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 raw OPTimIS text data through a set of nested text libraries that filter the text into activity categories and subcategories (see Figure 1).

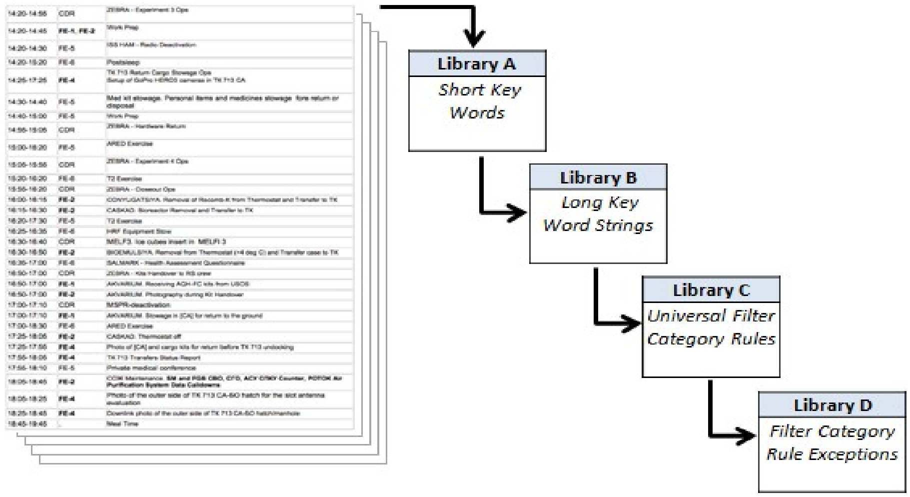

Figure 1. ECTM Categorization Library Process

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. Researchers developed a new data conditioning and analysis process to assess repair times for spacecraft system.

3. Repair Crew Time Data Conditioning

Crew repair time data is extracted from Maintenance Data Collection (MDC) 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. 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 is 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 14 categories, shown in Table 2 below. Grouping components into these 14 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.	Complex Air Assembly
5.	Complex Liquid Assembly
6.	Electronics
7.	Pump
8.	Sensor
9.	Tank
10.	Fan
11.	Filters
12.	Heat Sink
13.	Plumbing
14.	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, repairs, or any other maintenance conducted on a component that does not involve the component being replaced. 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 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.

4. Data Analysis

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 the components onboard operate 365 days a year, some component data for our analysis needs to be adjusted to reflect operating 28 days a year. 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 Surface Habitat (SH) is the sum of all the system schedule maintenance crew times.

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, some 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. 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.

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.

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]. 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 an accurate, data-driven crew time schedule can be created.

5. Surface Habitat Case Study

Component repair and maintenance time data, generated using the described process, was then used to develop 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.

SH Architecture

After determining crew time distributions for each component or component category on the ISS, the team derived POS crew times for repair on the SH. The team aligned the crew time distributions to the different components in the SH sub-system architecture. The baseline case for this study includes 20 different SH subsystems, listed in Table 3 below.

Table 2. SH Systems

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.	Fire Detection & Suppression (FD&S)
14.	Waste Management System (WMS)
15.	Electric and Power System (EPS)
16.	Comm. and Tracking (C&T)
17.	Command & Data Handling (C&DH)
18.	Active Thermal Control (ATCS)
19.	Airlock Gas Recovery System (ALGS)
20.	Exercise Systems

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 FD&S, EPS, C&T, and C&DH systems were analyzed as running 365 days a year and all other systems running 28 days a year.

The POS crew time for corrective maintenance times is shown in Figure 2. The results at each of the orange crosses is listed in Table 4.

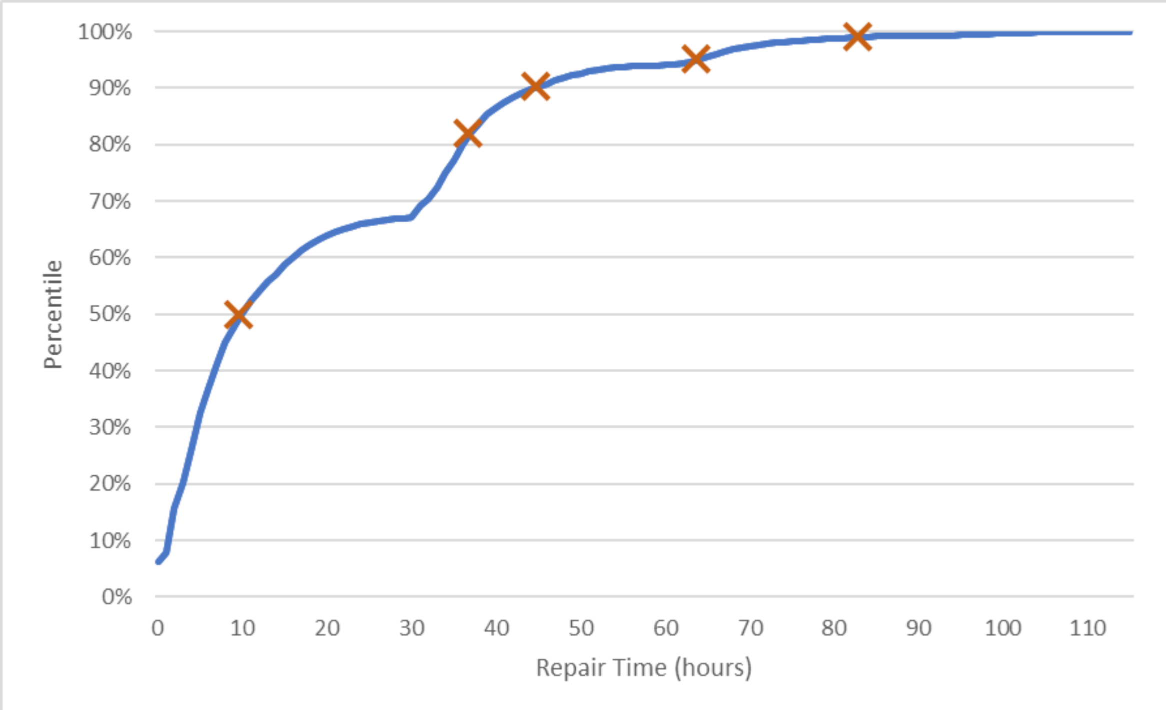

Figure 2. POS Maintenance Crew Time

Table 3. Select Percentiles for Distribution Analysis of Full Regenerative ECLSS

Percentile	Required Repair Time (hours)
50th	10
80th	37
90th	45
95th	64
99th	83

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 14 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.

Like the process described in the Data Conditioning section, SH components that have sufficient historical ISS maintenance data can use the MTTR and repair ratios calculated with its own component data, not component category data. Every component on board the SH had an MTTR and repair ratio calculated which was then fed into the Maintenance and Repair Model. The Maintenance and Repair Model calculated a probability distribution function for each component, which was summed to generate the total maintenance crew time probability distribution function. The POS maintenance crew time was then calculated as the CDF of this probability distribution function which is shown in Figure 2.

The results show a significant increase between the bottom 50% POS of 10 hours and the 99% POS value of 83 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. If this were to occur, it would likely limit the crew time available for utilization activities.

6. Conclusion and Future Work

The methodology of this analysis provides the most accurate results of crew time spent on maintenance and repair onboard the ISS and an accurate method to apply this information to predict repair time requirements for future missions. 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. HPO2 = 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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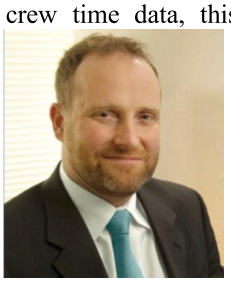
BIOGRAPHY



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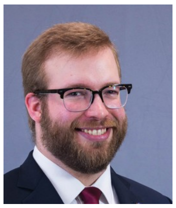

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