JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 1, January–February 2006

Applying Analysis of International Space Station Crew-Time Utilization to Mission Design

James F. Russell* and David M. Klaus†
University of Colorado, Boulder, Colorado 80309
and
Todd J. Mosher‡
Utah State University, Logan, Utah 84322

Science activity on the International Space Station (ISS) has been anecdotally reported to be less than expected, presumably because of excessive time being taken up by habitat maintenance needs. In this analysis, it was determined that each crew member spent an average of 1.9 (or more) h per work day and 1.8 h per rest day performing ISS maintenance tasks. Because of confounding factors associated with insufficient supplies and reduced transport opportunities, the relationship between mission design and actual operations is not necessarily simple or direct, as increased maintenance demands or a lack of up- and downmass for science projects may have both contributed to the crew-time impact. Regardless of the causal mechanisms, however, actual crew time spent on scheduled and unscheduled habitat maintenance on Skylab and ISS exceeded that estimated by design, thus reducing crew time allotted to perform other tasks, although not necessarily science tasks. These impacts would have likely been further exacerbated for ISS if the planned external maintenance tasks had not been reduced during the early design phase. The approach used for assessing external maintenance could be applied for other tasks, such as internal maintenance and science, to establish the amount of time required for mission goals and uncertainty factors. By rigorously addressing parameters such as these early in the design process, crews on future missions to the moon and Mars are less likely to become oversubscribed during actual mission operations.

I. Introduction

IN recent years, members of the press and U.S. Congress have questioned affiliated space-agency representatives about the crews' ability to adequately conduct the planned science activities onboard the International Space Station (ISS).[1–4] The specific concern has been that habitat maintenance demands (scheduled and unscheduled tasks) have diverted significant crew time away from fulfilling the research objectives. This concern of excessive space-habitat maintenance time is not unique to the ISS program and has the potential to affect future missions if not rigorously addressed in the early stages of design.

Historically, crew time for habitat maintenance has exceeded that specified by design for two reasons: greater amounts of scheduled maintenance occurring than originally intended and additional unexpected (therefore unscheduled) maintenance tasks arising. For example, maintenance time allocated for Skylab housekeeping increased from a planned duration of 0.75 h per crew member per day (hr/CM/d) to an actual average of 1.1 hr/CM/d (Table 1),[5,6] and unscheduled maintenance on both Skylab and Mir increased the crew time needed for habitat maintenance to roughly 4 hr/CM/d (Ref. 7). To accomplish these additional maintenance operations, crew time was diverted from other scheduled activities, such as sleep during some Mir missions, or they were carried out during handover and visiting operations when more crew members were onboard to assist.[7,8] To minimize the risk of spending more time than expected on maintenance during future exploration missions to the moon and Mars, it is important to consider how these activities can be optimized by habitat design factors.

A. Assessment of Crew Time Impact on Design

Incorporating crew-time requirements into the habitat design process first and foremost requires that accurate estimates be made for equipment maintenance frequency and operational crew-time demands. Furthermore, operational estimates must include the time to perform the actual task (e.g., filter replacement) and to accommodate any supporting logistics (e.g., tool relocation, work site prep/tear down, filter disposal). This can be either estimated from task durations measured during terrestrial simulations or directly calculated from similar activities reported on previous space missions. Records from past missions can be obtained from ISS-affiliated governmental space agencies in documents such as the ISS task log (On Board Short Term Plan) as was used for this study.

Crew time required for maintaining each spacecraft subsystem can be derived from actual or estimated values and validated during the early phases of habitat design.[9,10] Incorporating activity levels realistically needed for planned operational maintenance tasks will allow spacecraft designers to optimize usage of the crew in conjunction with other important trade factors such as system mass, power, and reliability. In support of this approach, ISS habitat maintenance was systematically characterized as a fraction of crew workday, and the impact of decreased crew time during independent operations (excluding joint operations with visitors or handover crews) on ISS's overall operation was assessed to support the design of moon and Mars missions.

B. Division of Time: Earth and Space

A definition of crew time and division of daily task allocations is a necessary precursor to making informed spacecraft habitat design choices. On Earth, as during spaceflight, natural divisions exist in daily activities between required and optional tasks. The three major terrestrial-activity categories for working adults are considered for this analysis to be salary-based work, personal maintenance, and housework. Salary-based work is that which is typically performed

---

Received 23 February 2005; revision received 16 May 2005; accepted for publication 16 May 2005.

*Ph.D. Candidate, Aerospace Engineering Sciences, UCB 429. Student Member AIAA.

†Assistant Professor, Aerospace Engineering Sciences, UCB 429. Member AIAA.

‡Assistant Professor, Mechanical and Aerospace Engineering. Associate Fellow AIAA.

Table 1 Comparison of an average work day for men and women of 18–64 years in California in 1987/1988 as reviewed by the Environmental Protection Agency to the average work day on Skylab over the three manned missions in 1973 and 1974[4,5]

General category	California study,[a] hr/person/24hr-d, $n = 1359$		Skylab,[b] hr/crew member/24hr-d, $n = 12$	
Salary-based work mission operations	Paid work:	4.5	Medical activities and experiments:	6.1
	Education/training:	0.4		
	Organization activities:	0.2		
	Total:	5.1	Total:	6.1
Personal maintenance	Personal needs:	10.7	Sleep/rest and off duty:	7.6
	Social:	1.0	Pre/postsleep and eating:	5.7
	Recreation:	0.7	Exercise/hygiene:	1.3
	Communication:	3.4		
	Total:	15.8	Total:	14.6
Housework habitat maintenance	Household work:	1.7	Housekeeping:	1.1
	Logistics:	1.0	Other (e.g., EVA)[c]:	2.2
	Child care:	0.4		
	Total:	3.1	Total:	3.3

[a]The sampled population includes parents whose primary job is child care and who may or may not engage in any paid work.
[b]The standard deviation of Skylab data was not reported.
[c]The subcategory "Other" includes some tasks that might be considered mission operations and not habitat maintenance.

as a job for pay. Personal maintenance falls into a gray area between required and optional activities, as sleeping, eating, and exercising are required to stay healthy, but can be occasionally skipped or reduced without significant consequence. Housework, though, is generally optional on any given day because scheduled maintenance needs and even functional repairs are normally not directly threatening to life or habitat. Based on these categorical divisions, salary-based work is required and, as such, is usually given the highest priority. Therefore, decisions that influence a person's day-to-day planning would likely revolve around salary-based work (if the person is in the labor force). On a spacecraft, the crews' work days are generally structured in a manner similar to terrestrial divisions (Table 1); however, required tasks necessarily alter the priority ranking of the categories because in this case their neglect can be catastrophic.

Similar to the three terrestrial categories just described, for this study space crew tasks were assigned to one of three activity categories: mission operations (MisOp), personal maintenance (PeMtn), or habitat maintenance (HabMtn). These spaceflight categories are roughly equivalent to salary-based work, personal maintenance and housekeeping, respectively, but are unavoidably more regimented. For example, the minimum program requirement for ISS utilization operations (i.e., science) is 20 hr/wk (Ref. 11), but these activities are typically assigned lower priority than those needed for habitat and personal maintenance tasks. Personal maintenance in space is important and generally scheduled as a fixed value because too little sleep or exercise can negatively affect performance efficiency and can even cause life-threatening errors.[8] Habitat maintenance is composed of scheduled (e.g., cleaning filters) and unscheduled tasks (e.g., component repairs) and is critical for maintaining a safe and healthy environment for the crew. Because of the potential seriousness of system failures, habitat maintenance must be given high priority on a spacecraft, but, unfortunately, this demand frequently conflicts with other required mission operations. Therefore, to successfully meet the overall goals of future space missions, design and operational decisions need to concurrently address the time needed to conduct habitat maintenance tasks and optimize crew-time allocation based on realistic expectations.

II. Data and Methods

The following equation is used to characterize the fraction of a day that each crew member (CM) spends in one of these activity categories:

$$24\ \text{hr/CM/d} = \text{MisOp} + \text{HabMtn} + \text{PeMtn} \tag{1}$$

Values for each category can be obtained from one of three reported sources. First, actual crew time is recorded by the crew or ground personnel as the time spent on an activity on a specific day. The second source is planned crew time, which is the time per activity scheduled jointly by the crew time schedulers (increment engineers) and the crew. This crew time is documented in a computer program called the On Board Short Term Plan (OSTP) and in the Russian Form-24. The third source, required crew time, is defined by the ISS Program Generic Ground Rules, Requirements, and Constraints (ISS-Ground-Rules) document. The document specifies the required level of activities as the total hours per week (hr/wk) or hours per crew member per day (hr/CM/d) by the program office.[11]

A. Required Crew Time on ISS

The 16 countries making up the ISS consortium have agreed upon guidelines for the use of crew time on the station. This agreement is embodied in the ISS-Ground-Rules document, which has been refined 10 times over the past two years.[11] The current version of the ISS-Ground-Rules document provides specific details about certain crew activities and their associated crew-time demands. These activities represent required crew time and are related to the three categories shown in Table 2. The preceding relationships were used in this study to examine actual crew time and how expenditures compared to stated requirements.

B. Actual Crew Time and Planned Crew Time on ISS for Increments 4–8

The required crew activities of most concern to increment engineers are the technical work entailed by mission operations and habitat maintenance. These tasks must be conducted on the five work days as well as the two rest days allocated per week. With a focus on these activities, each increment engineer is in charge of creating the planned crew-time schedule and documenting the actual crew time reported during this period. An increment is currently about six months for two or three crew members, beginning the day the new crew docks and ending when the replacement crew arrives. After the increment is completed, the increment engineer documents the technical work in a Post Increment Evaluation Report based on actual crew time values obtained from the OSTP.

The ISS Program Office provided the actual crew time from the OSTP for increments 4 to 8 for this study. Of these five increments, however, only increment 4 has been fully reviewed by the increment engineer. Knowing that some records of crew time might be missing from the information, a preliminary analysis was conducted to assess completeness of the data. From this, it was found that only a little more than 50% of each workday was documented because of the need of increment engineers to only assign technical work. A fuller accounting of actual crew activities was required for thorough analysis of an average 24-h day on the ISS.

Table 2 Required crew time from the ISS-Ground-Rules document placed into one of three activity categories on workday and rest days[10]

General category	Required crew time on a work day, hr/CM/24hr-d		Required crew time during the work shift on a work day, hr/wk	
Mission operations	Planning and coordination:	0.5	Medical operations:	12.0
	Work preparation:	1.5	Onboard training:	4.0
	Work shift (shared):	6.5	Public affairs office:	<4.5
	Total:	≤8.5	Utilization operations:	>20.0
Personal maintenance	Presleep:	2.0	Not applicable	
	Sleep:	8.5		
	Postsleep:	1.5		
	Exercise:	2.5		
	Midday meal:	1.0		
	Total:	15.5		
Habitat maintenance	Work shift (shared):	6.5	Housekeeping (per CM): on the two rest days per week	4.0
	Shared:	≤6.5		

Removal of Progress Docking Mechanism: Biochemical Blood Test

GMT	Crew	Activity
06:00 – 06:10		Morning Inspection
06:10 – 06:40		Post-sleep
06:40 – 07:00		Biochemical blood test

Fig. 1 Excerpt from expedition crew flight plan (from 24) for the ISS on 4 February 2002 during increment 4.

Documentation of planned crew time offers a potential data source to account for the unassigned periods in the actual crew-time log. The source of this information is publicly available via Russian Form-24 (Fig. 1), which covers the same tasks as the OSTP.[§] A potential concern with using this approach, however, is the realization that nondocumented differences have occurred between planned and actual activities, but because systematic differences were used to account for the unassigned times this correction methodology was unbiased.

To begin comparing planned and actual crew time, the average number of hours spent per crew member per day (hr/CM/d) in each activity category for the five different increments was determined. Then a one-way analysis of variance of these average workdays was completed using the statistical analysis software, GraphPad Prism™ 4. This analysis revealed that each increment's average work day was statistically different from the other increments in at least one of the three activity categories (personal maintenance, habitat maintenance, or mission operations), and so the comparison required random sampling of work days from each increment. The necessary sample size n_m for the paired workdays was determined using the following equation[12]:

$$n_m = \frac{(\sigma^2)(Z_{1-\alpha} + Z_{1-\beta})^2}{(\mathrm{MDC}^2)} \tag{2}$$

where MDC is the minimum detectable change in size, $Z_{1-\alpha}$ is the Z coefficient for the type I error ($\alpha = 0.05$), $Z_{1-\beta}$ is the Z coefficient for the type II error ($\beta = 0.10$), and σ is the standard deviation of the sample.

The sample size was computed as seven work days for each increment, 35 days total, to be randomly selected. For the selected workdays, the tasks were organized and standardized to match with the OSTP format. Using compatible formats, planned and actual crew times were compared in Microsoft Access™ to determine the time spent on tasks not documented by the increment engineers. Given that the increment engineers concentrated on technical work, it was not surprising that sleep, postsleep, and presleep periods were often missing. Based on a day-by-day assessment of both work days and rest days, the missing tasks of sleep, postsleep, and presleep were added to the actual crew time per increment to represent a full day.

C. Systematic Deviations

After filling in gaps missing from the actual crew-time logs, the data were analyzed for systematic deviations. The two potential systematic factors of most concern were the reduction in the number of crew members onboard the ISS during the period of study (from three to two) affecting categorical task performance averages and the change in human performance affecting task times from the first quarter to last quarter of each increment. For these analyses, the Mann–Whitney rank sum test, a nonparametric, two-tailed test was used to determine if the median times from each category were significantly different. This statistical comparison used a 95% confidence (p-value cutoff of 0.05), which indicates that the median results for 95% or more of the population will differ significantly based on the sample analysis. The outcome is reported as modified actual crew time (MACT).

III. Results Based on Modified, Actual Crew Time

MACT is intended to represent a 24-h day on the ISS. For the purposes of this analysis, only the 792 days of independent operations (i.e., no visitors present) were examined to best provide insight into conditions that might be expected during exploration missions to the moon (Table 3). Sometimes independent operations required schedule shifts to accommodate certain intravehicular and extravehicular activities, such as progress docking. On these off-nominal days for various reasons the total daily scheduled time could be less than 22.9 h per day or greater than 25.1 h per day. Seventy-one days were, therefore, identified as off nominal and treated as outliers, with the remaining 721 nominal days from increments 4 to 8 used in the analyses. Before an average day for these increments can be discussed, sources of recording inaccuracies had to be identified, and the impact of random and systematic sources of deviation must be addressed.

A. Possible Sources of Recording Inaccuracies

The recording process itself for logging actual crew time has the potential for introducing inaccuracies. Tasks are either recorded by the ISS crew as "Completed" status, or by mission operations personnel as "Scheduled Enabled" status as a method to indicate task completion. The tasks reported as Scheduled Enabled account for 49% of actual crew time for technical work on workdays, or approximately 4 hr/CM/d. With an S communications band (S-band) availability of 46%, voice communication with the ISS crew is periodically lost. This loss of S-band can affect reporting accuracy of Scheduled Enabled tasks if it exceeds 5 min (the smallest unit of documented time); therefore, these periods of signal loss are of concern.[13,14] Because of this signal loss and the primary focus of

[§]Dismukes, K., "Expedition Crew Flight Plans for the International Space Station" [online database], URL: http://spaceflight.nasa.gov/station/timelines/ [cited 2 July 2004].

Table 3 Summary of the characteristics of actual crew time for increments 4–8

Increment	4	5	6	7	8	Total
Long-term crew size	3	3	3	2	2	13
Recorded vs known stay, d	175/191	176/179	159/159	183/183	193/193	886/905
Workdays for independent operations, d	108	101	101	115	121	546/792
Rest days for independent operations, d	48	44	45	54	55	246/792
Other days with visitors or during handover periods, d	19	31	13	14	17	94

Table 4 Comparison of average work days during the beginning and end of independent operations during increments 4–8 with the Mann–Whitney rank sum test

General category	1st quarter, hr/CM/d, $n = 122$	4th quarter, hr/CM/d, $n = 122$	Statistically different?
Habitat maintenance	2.2 ± 1.5	2.2 ± 1.4	No ($p = 0.93$)
Mission operations	5.5 ± 1.6	5.7 ± 1.5	No ($p = 0.25$)
Personal maintenance	15.3 ± 0.8	15.4 ± 1.0	No ($p = 0.72$)
Unassigned	1.0	0.8	——

recording completed tasks, the crew-time records used represent a best estimate of crew time expended for a given task.

Another potential for recording inaccuracy is the variable reporting of crew time in a multitasking environment. On ISS, a crew member can potentially work on several tasks at once, depending on the nature and complexity of the activities. When reporting the crew time associated with two or more overlapping tasks, double counting is possible. For the purposes of this analysis, it was assumed that actual crew time represented the time spent actively working on each given task.

B. Systematic Deviations

These two potential systematic factors were analyzed using standard statistical methods. The data were first examined for systematic error attributable to a change in human performance with the Mann–Whitney rank sum test. For a work day during independent operations, the statistical test indicated that the medians of the three major categories were not significantly different ($p < 0.05$) between the first and last quarter of the five increments; results are summarized in Table 4. Based on this result, reported crew time, and thus inferred crew performance efficiencies, did not appear to produce a systematic error in the three general activity categories, although there can still be variations on individual task levels.

The main factor of concern, however, is the reduction from three to two crew members that occurred on ISS during the period of study. An average day for increments 4–6 with three crew members was compared to the average day for increments 7 and 8 with two crew members using Mann–Whitney rank sum tests (Table 5). The six nonparametric, two-tailed tests showed a significant difference between the two crew types in at least one category on work days and rest days. This indicates that the shift from three to two crew members caused a change in use that can be attributable to a reduced workforce. Therefore, the results of the MACT were quantified for three CM and two CM separately for the three major activity categories (mission operations, personal maintenance, and habitat maintenance) and their respective subcategories. Each category is represented as an average and one standard deviation, assuming a normally distributed data set. Some of these categories, however, are not normally distributed and could not be transformed to a normal distribution because of the presence of zero values. Therefore, an artifact of the analysis is that some results appear to be less than zero at one standard deviation.

C. Mission Operations

Mission operations were quantified for the increments with three CM and two CM and summarized for the daily subcategories of planning and coordination, work prep, and work shift in Table 6. The mission operations work was also quantified for the weekly subcategories of medical operations, onboard training, public affairs office, and use operations summarized in Table 7. The large variability in the weekly estimates of crew time is caused by the propagation of errors that stems from using the average crew time for work days and rest days. This variability should not be directly interpreted as the amount of variation in weekly duties on the ISS.

Table 5 Comparison of average work days and rest days during independent operations with the Mann–Whitney rank sum test

Day	General category (subcategory)	3 CM, hr/CM/d	2CM, hr/CM/d	Statistically different?
Work day		$n = 272$	$n = 222$	
	Habitat maintenance	1.9 ± 1.2	2.4 ± 1.5	Yes ($p < 0.0001$)
	ECLSS[a]	0.5 ± 0.5	0.7 ± 0.7	
	Mission operations	5.9 ± 1.6	5.6 ± 1.6	Yes ($p = 0.03$)
	Personal maintenance	15.3 ± 0.9	15.4 ± 0.7	No ($p = 0.16$)
	Exercise	2.3 ± 0.3	2.2 ± 0.5	
	Unassigned	0.9	0.6	——
Rest day		$n = 124$	$n = 103$	
	Habitat maintenance	1.9 ± 1.5	1.8 ± 1.5	No ($p = 0.99$)
	ECLSS[a]	1.3 ± 1.4	1.5 ± 1.5	
	Mission operations	2.0 ± 1.0	1.3 ± 0.6	Yes ($p < 0.0001$)
	Personal maintenance	15.6 ± 0.9	15.7 ± 0.7	No ($p = 0.71$)
	Exercise	2.4 ± 0.4	2.2 ± 0.5	
	Unassigned	4.5[b]	5.2[b]	——

[a]Crew time for ECLSS was determined based on a general review of tasks for the three years of data, and so there was potentially more crew time in habitat maintenance spent on ECLSS maintenance then captured by our analysis.
[b]Unassigned time on the rest day is caused by the off-duty time because all of the technical work on these days is already documented.

Table 6 Comparison of allotted crew time to mission operations work on an average work day and rest day during independent operations

Day	Allotted crew time, hr/CM/d		3 CM, hr/CM/d	2CM, hr/CM/d
Work day			$n = 272$	$n = 222$
	Mission operations:	≤ 8.5	5.9 ± 1.6	5.6 ± 1.6
	Plan/coordination:	0.5	0.5 ± 0.2	0.5 ± 0.1
	Work prep[a]:	1.5	1.2 ± 0.3	1.1 ± 0.3
	Work shift[b]:	6.5	4.3 ± 1.6	4.1 ± 1.6
Rest day			$n = 124$	$n = 103$
	Mission operations:	0.4–0.7	2.0 ± 1.0	1.3 ± 0.6
	Plan/coordination:	0.0	0.2 ± 0.2	0.4 ± 0.2
	Work prep[a]:	0.0	0.5 ± 0.5	0.5 ± 0.5
	Work shift[b,c]:	0.4–0.7	1.2 ± 0.9	0.4 ± 0.4

[a]Work prep is the time allotted for preparing to conduct mission operations and habitat maintenance activities.
[b]Work shift is the combination of activities in mission operations and habitat maintenance.
[c]On rest days, the crew works 80 min (or as required) to conduct status checks on science payloads. For three crew members, this equates to 0.4 hr/CM/day, and for two crew members this equates to 0.7 hr/CM/day.

D. Personal Maintenance

Personal maintenance was also quantified for the increments with three CM and two CM. In these increments, the three main

Table 7 Average amount of mission operations and habitat maintenance work for a week during independent operations

General category	Required weekly work shift, hr/wk		3 CM,[a] hr/wk	2 CM,[a] hr/wk
Mission operations	Medical operations[b]:	~12.0	10.0 ± 11.1	7.0 ± 7.0
	Onboard training[b]:	~4.0	4.1 ± 10.6	2.4 ± 6.1
	Public affairs office:	< 4.5	3.4 ± 5.1	2.5 ± 3.5
	Use operations:	> 20.0	18.4 ± 15.3[c]	12.9 ± 11.7[c]
	U.S. science:	17.5	13.0–14.7[d]	7.3–9.5[d]
Habitat maintenance	Housekeeping:	8–12	15.5 ± 16.0	13.0 ± 12.3
	——	−4.0/CM	−5.2 ± 5.3/CM	−6.5 ± 6.2/CM

[a]Weekly values for crew time were calculated by multiplying the average work day value by 5 and the average rest day by 2 and then adding these two values together.
[b]Training for medical operations is included in medical operations not in onboard training.
[c]We determined the use operations for weekly use from our interpretation of the task categories.
[d]NASA calculates the crew time used by the United States for research per week on ISS; the range of crew time is shown for increments 0 to 8. Higher use of crew time for research is possible, if there were sufficient supplies on ISS and transport opportunities to ISS.[14]

subcategories of personal maintenance (sleep, postsleep, and presleep) were missing for some days, and so these subcategories were added to create a fuller accounting and better understanding of actual crew time per day. Because of the possible deviation between planned and actual crew time just described, crew times for these three sleep subcategories were individually quantified. The other two categories of midday meal and exercise were quantified, and the time for exercise is shown in Table 5.

E. Habitat Maintenance

Finally, habitat maintenance was quantified for the increments with three CM and two CM to determine the average daily and weekly amount of housekeeping, which was found to primarily be the crew time needed for environmental control and life support maintenance (ECLSS) (Tables 5 and 7). As stated for mission operations, the variability in the data should not be directly interpreted as the amount of variation in weekly duties on the ISS.

IV. Discussion

MACT was created to account for full reporting of a 24-h day on the ISS during independent operations. From these data, an average daily and weekly use of ISS crew time was quantified for independent operations conducted during increments 4–8. These averages were then used to examine the data with respect to ISS program requirements (as documented in the ISS-Ground-Rules document) and to address the significance of time spent on habitat maintenance.

A. Breakdown of Crew Time on ISS

MACT was analyzed first in terms of the activity categories identified as personal maintenance, mission operations, and habitat maintenance. These major categories were then divided into the subcategories specified in the ISS-Ground-Rules document.

1. *Personal Maintenance*

In the major category of personal maintenance, the MACT (see Table 5) was within 0.2 h of the daily allotted time for crew members for the whole study period (see Table 2). Comparison of MACT to crew time required for the subcategories of sleep, postsleep, presleep, and midday meal was not conducted because these subcategories were not normally tracked by the increment engineers. The only subcategory to be fully documented was exercise. Exercise time decreased when the crew size decreased from three to two CM because of problems with some of the exercise equipment (see Table 5). Without regular resupply missions from the shuttle in this time frame, the malfunctioning exercise equipment had to be serviced on orbit, which, as a consequence, required additional crew time for maintenance and left less time for exercise. In the microgravity environment, reducing the time available for exercise also decreased the fitness of the crew. In fact, the cosmonauts who were onboard ISS without fully functioning exercise equipment were reported to have lost more muscle than was average for cosmonauts spending comparable time on Mir.[15] Based on the combined undesirable outcome of increased maintenance time demands and reduced fitness levels, designers of future space habitats need to thoroughly consider the impact of crew equipment failure on overall mission success.

2. *Mission Operations*

Mission operations for ISS are given as weekly required crew time in the areas of medical operations, onboard training, public affairs (news/press), and utilization operations (science) (see Table 2). Analysis of the MACT for mission operations shows a significant decrease ($p = 0.03$) of 0.3 h in total daily time spent accomplishing these objectives with the shift from three CM to two CM (see Table 5). The decrease in crew time for mission operations impacted the weekly average of the four subcategories (Table 7). Prior to the shift from the three CM to two CM, the average weekly time that the three crew members spent in all four categories was within 2 h of the required crew time. After the shift, the two crew members had even greater difficulty in meeting the required crew time. Given insufficient supplies on the ISS and reduced transport opportunities to the ISS, crew time for mission operations might have been reduced because of increased maintenance or a lack of materials to conduct utilization operations (science).[16]

3. *Habitat Maintenance*

In the ISS-Ground-Rules document, most of the requirements pertain to the allotment of crew time for personal maintenance and mission operations.[11] Only one requirement from this document, housekeeping, relates to habitat maintenance. However, habitat maintenance becomes the driving category of the crew time on missions where crew time is limited because it can considerably impact the crew time available for science or other activities.

After the ISS crew was reduced to two members, MACT increased by 0.5 h for habitat maintenance, whereas mission operations decreased by 0.3 h during the work week (see Table 5). To understand the cause of this shift, we examined a major contributor of habitat maintenance, space-station housekeeping (see Table 5). A housekeeping requirement of 4.0 hr/CM/wk (or less) was allotted for maintaining ECLSS. During the nominal three-CM period, this requirement was exceeded by each crew member working approximately 5.2 hr/wk, and it was further exceeded by an additional 1.3 hr/wk during the period when only two crew members were onboard (see Table 7). This was an unexpected finding, as the consumable demand for ECLSS was proportionally reduced with one less crew member present. When comparing the two periods, however, the MACT for ECLSS maintenance was found to have decreased only 2.5 hr/wk (see Table 7). If all other factors were constant, this suggests the presence of an ECLSS overhead cost, which is reflected by the amount of crew time required for housekeeping, and one that is independent of the number of crew members.

However, ECLSS maintenance was not constant from increment 4 to 8. There were startup issues with the carbon-dioxide removal assembly and the lack of shuttle missions in this time frame led to limited resupply opportunities and replacement part provisioning.[17–19] In addition, there were problems with the Elektron system that was designed to continuously electrolyze water into oxygen with 32 A of electrical current (or at a reduced state of 24 A) to maintain acceptable oxygen levels in the cabin.[20,21] In practice, the Elektron was operated continuously or manually from 0 A (off) to the maximum setting of 64 A (Refs. 21 and 22). Operating the Elektron continuously was difficult because of power and air/water separation issues. The first limiting factor was that the ISS lacked sufficient power to continuously run this system in parallel with other required-powered devices.[21] The second factor was that problems with proper air-water separation caused the unit to malfunction. To reduce bubbles in the water tank (and thus reduce the need for air-water separation), the crew had to spend extra time each week to minimize bubble formation in the Elektron's water supply unit. They also spent time during increments 4–8 installing a new air-water separator and several new fluid units.[18] Because of the issues arising from the continuous operating mode, the unit was sometimes manually operated with other systems that were powered down as required. As demonstrated by the preceding examples, establishing a direct link between maintenance and crew size is confounded by unanticipated ECLSS operational modes.

B. Design vs Operation

The shift in crew size from three CM to two CM and reduced transport opportunities impacted the operation of the ISS. The analysis of these impacts revealed a mismatch between the intended design and associated crew-time demands. This disparity was complicated to some extent by the fact that the ISS was designed as an orbital research facility to eventually hold six or seven crew members. Therefore, the operational time demands for maintenance were increased per crew member with a smaller labor force, which further reduced available crew time for other activities. Given the recent change in program priorities and current limitations on human-rated launch vehicles, the crew size is expected to remain at three CM for the near term, but is planned to increase to six CM when the life-support module, the habitat module, and a second Soyuz lifeboat are added.[18] Characterizing the effects resulting from these crew size fluctuations offers validated insight regarding operational sensitivity factors for future vehicle and mission designs.

C. Application of Uncertainty Analysis to Future Space Mission Design Optimization

Future space missions, such as lunar or Mars exploration, likely will be designed in a similar fashion to the ISS. The ISS was designed to minimize cost by reducing mass and to reduce risk by increasing reliability of equipment and incorporating dissimilar redundancy; however, these approaches have potential flaws. Crew time required for scheduled in-flight maintenance of internal ISS equipment was not a major design driver, which might have been caused in part by the limited number of technology alternatives available for ECLSS.[18,23] Furthermore, although the overall ISS design concentrated on increasing reliability, design of the internal systems appears to have not sufficiently considered the impact of system reliability on crew time (i.e., unscheduled in-flight maintenance).[11] For example, the design of the ECLSS for the ISS estimated 50.0 hr/yr of crew time (or 1.0 hr/wk),[20] but crew time actually needed for scheduled and unscheduled maintenance on the ISS has exceeded this value by a factor of 13–15 times. If this same unintended outcome were to occur on future missions, a considerable amount of excess habitat maintenance time might be required that could have been used for other objectives.

To help ensure that sufficient crew time exists to meet the goals of future space missions, therefore, crew-time requirements for internal and external maintenance of ECLSS, science payloads, and other equipment need to be considered early during the design process.[24] The early phases of design traditionally select optimal systems by trading off mass, cost, and other parameters. Crew-time factors could be more fully incorporated into the design process by following the method outlined in Fig. 2. The two critical aspects of this initial decision-making method are 1) determining the value of crew time and 2) properly calculating the crew time needed (i.e., operational crew time). Crew time can be estimated by using a general parametric model based on previously documented similar activities. One relevant example of this approach is the extravehicular maintenance assessment conducted for the early design of the International Space Station, then known as Space Station *Freedom*.[9,10] Following this method, crew-time analysis can be effectively applied to the design of future space missions in terms of assembly, maintenance, and science activities.

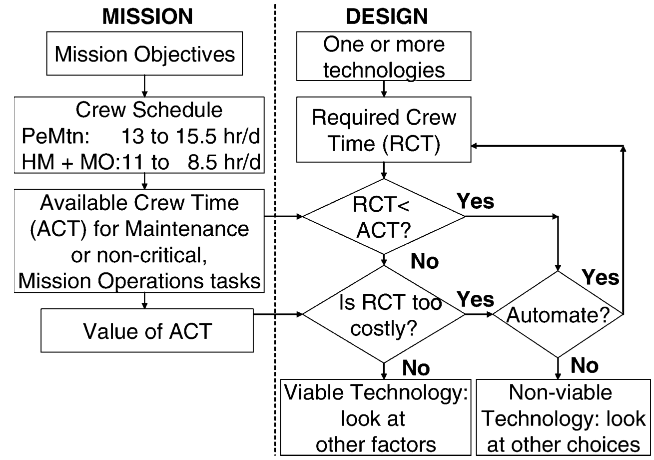

Fig. 2 Decision tree for the consideration of crew time in technology selection. This figure is proposed for use by designers of exploration missions during the technology selection process. This same process can be applied to science selection, for example, in deciding between in situ analysis or downmass of samples for analysis.

The basic methodology proposed here addresses crew time, but neglects the impact of uncertainty in vehicle and mission design. As seen from the external maintenance task report and actual operations on ISS, the optimization of vehicle and mission designs should also include several categories of uncertainty, such as technology reliability, crew performance, and vehicle availability.[10] By identifying and incorporating the relevant uncertainty factors, risk associated with a given design can be quantified. Inaccurate estimates of these uncertainties (and their interactions), however, will propagate through the design and provide an inaccurate estimate of the risk. Therefore, better estimates of crew time and uncertainties will allow for improved optimization of vehicle and mission design with respect to risk. Based on our observations of Skylab and ISS operations, we recommend that a given technology selection be assessed based on the uncertainties in technology parameters (e.g., crew time, reliability) and mission parameters (e.g., available power).

V. Conclusions

Crew time for ISS habitat maintenance took on average 1.9 hr/CM/d and 2.4 hr/CM/d for the three CM and two CM periods, respectively, representing a considerable part of each work day. A major component of this time was determined to arise from ECLSS maintenance. The MACT for ECLSS maintenance exceeded the crew time calculated from the design by an order of magnitude, which suggests better estimates and validations of operational crew time for ECLSS are needed. Because of confounding factors of insufficient onboard supplies and reduced transport opportunities, the relation between mission design and operations for ECLSS is not simple or direct. Other potential factors include increased maintenance or a lack of up- and downmass for science projects. Regardless of the causal mechanisms, actual crew time spent on scheduled and unscheduled habitat maintenance on Skylab and the ISS exceeded that estimated by design, thus impacted the crew time allotted to perform other tasks, not necessarily just science. This recurring phenomenon implies that human space mission designers need to thoroughly establish the amount of time required for vehicle maintenance and the associated uncertainty in mission parameters early in the design process (preoperations) to avoid similarly oversubscribing future crews.

Overall, the analysis of actual crew-time allocation on recent ISS increments indicates that habitat maintenance poses a potential topic of concern for mission designers. Therefore, the crew time required for technology maintenance and the impact of this maintenance on mission goals warrants additional consideration.

Acknowledgments

We acknowledge the contributions of Kathleen Leary, Hugh Jamison, and Daniel Celik of the International Space Station Program Office at Johnson Space Center in Houston, Texas, for providing the actual crew-time data for increments 4–8 and obtaining the approval for public release of the data. We also acknowledge Darwin Poritz of the Advanced Life Support System Program at Johnson Space Center in Houston, Texas, for his comments on the statistical analysis.

References

[1]Bond, P., *The Continuing Story of the International Space Station*, 1st ed., Praxis Publishing, New York, 2002, pp. 233–236, 279.

[2]Pianin, E., and Sawyer, K., “Space Station Mission Opposed: Despite Safety Concerns of Some Experts, NASA Decided to Send New Crew,” *Washington Post*, No. 322, 23 Oct. 2003, p. A9.

[3]Lawler, A., “NASA’s Plan for Station: From Lemon to Lemonade,” *Science*, Vol. 303, No. 5658, 2004, pp. 615–617.

[4]U.S. Congressional House of Representatives, Committee on Science, “The Future of Human Space Flight,” Hearing, 16 Oct. 2003, 108th Congress, 1st Session, Government Printing Office, Washington, DC, 2003, Serial 108-29.

[5]“Exposure Factors Handbook,” Office of Research and Development, U.S. Environmental Protection Agency, EPA 600/P-95/002Fa, Washington, DC, Aug. 1997, Chap. 15, pp. 15–24.

[6]Clark, J. W., “MSFC Skylab Mission Report—Saturn Workshop,” NASA TM X-64814, Oct. 1974.

[7]Shayler, D. J., *Skylab: America’s Space Station*, edited by J. Mason, Astronomy and Space Sciences, Springer-Praxis Books, New York, 2001, pp. 78, 353, 354.

[8]Nechaev, A. P., “Work and Rest Planning as a Way of Crew Member Error Management,” *Acta Astronautica*, Vol. 49, No. 3–10, 2001, pp. 271–278.

[9]Fragola, J. R., and McFadden, R. H., “External Maintenance Rate Prediction and Design Concepts for High Reliability and Availability on Space Station Freedom,” *Reliability Engineering and System Safety*, Vol. 49, No. 3, 1995, pp. 255–273.

[10]Fisher, W. F., and Price, C. R., “Space Station Freedom External Maintenance Task Team,” NASA TM-111430, July 1990.

[11]United Space Alliance, “International Space Station Program Generic Groundrules, Requirements, and Constraints Part 1: Strategic and Tactical Planning,” NASA/RSA/NASDA/ESA/CSA/ASI SSP 50261-01 RevA, 1998, pp. 1–91 [plus Official Updates DCN 001 (2001)–DCN 010, Aug. 2003].

[12]Kupper, L. L., and Hafner, K. B., “How Appropriate Are Popular Sample Size Formulas,” *American Statistician*, Vol. 43, No. 2, 1989, pp. 101–105.

[13]Kelly, T., *Engineering Challenges to the Long-term Operation of the International Space Station*, National Academy Press, Washington, DC, 2000, p. 24.

[14]Jorgensen, C. A., “International Space Station Evolution Data Book: Volume I. Baseline Design,” NASA SP-2000-6109/VOL1/REV1, Oct. 2000, pp. 3–22, 3–23, 4–41.

[15]Kozlovskaya, I. B., and Grigoriev, A. I., “Russian System of Countermeasures on Board of the International Space Station (ISS): The First Results,” *Acta Astronautica*, Vol. 55, No. 3–9, 2004, pp. 233–237.

[16]Larson, K., and Harris, E., “Crewtime and Resource Utilization for the Human Research Facility on the International Space Station,” *Proceedings of Space 2004 Conference and Exhibit* [CD-ROM], Vol. 9, No. 20, AIAA, Reston, VA, 2004.

[17]Gentry, G. J., Reysa, R. P., and Lewis, J. F., “International Space Station (ISS) Environmental Control and Life Support (ECLS) System Equipment: Failures, Causes, and Solutions February 2001–February 2002,” Society of Automotive Engineers, Paper 2002-01-2495, July 2002.

[18]Williams, D. E., Lewis, J. F., and Gentry, G., “International Space Station Environmental Control and Life Support System Equipment: 2002–2003,” Society of Automotive Engineers, Paper 2003-01-2589, July 2003.

[19]Gentry, G., and Williams, D. E., “International Space Station Environmental Control and Life Support System Equipment: 2003-2004,” Society of Automotive Engineers, Paper 2004-01-2382, July 2004.

[20]Wieland, P., “Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station: Volume 1,” NASA TM-206956, Jan. 1998.

[21]Philistine, C. L., “International Space Station Water Use for Oxygen Generation,” Society of Automotive Engineers, Paper 2004-01-2449, July 2004.

[22]Samsonov, N. M., Kurmazenko, E. A., Gavrilov, L. I., Farafonov, N. S., Pavlova, N. V., Pavlova, T. N., Proshkin, V. Ju., Romanov, S. Ju., Rjabkin, A. M., Guzenberg, A. S., Slyshchenkov, A. N., and Kirjushin, O. V., “Operation Results Onboard the International Space Station and Development Tendency of Atmosphere Revitalization and Monitoring System,” Society of Automotive Engineers, Paper 2004-01-2494, July 2004.

[23]Jones, H., “Multiple Metrics for Advanced Life Support,” Society of Automotive Engineers, Paper 1999-01-2079, July 1999.

[24]Klaus, D., Chluda, H., Ellis, T., Fehring, J., Howard, H., Jairala, J., Lloyd, T., Matthews, D., Morris, K., Rowley, K., Sauers, C., and Stephens, T., “Systems Engineering Evaluation of a Mars Habitat Design,” Society of Automotive Engineers, Paper 2004-01-2372, July 2004.

J. Korte
Associate Editor