AIAA Paper No. 72-232

③

AIAA PAPER 72-232

A SPACE MAINTAINABILITY EXPERIMENT ABOARD THE BEN FRANKLIN SUBMERSIBLE DURING THE 30-DAY GULF STREAM DRIFT MISSION

by
JOHN R. KAPPLER
Grumman Aerospace Corporation
Bethpage, New York
and
CHESTER B. MAY
NASA Manned Space Flight Center
Huntsville, Alabama

AIAA Man's Role in Space Conference

COCOA BEACH, FLORIDA/MARCH 27-28, 1972

Note: This paper available at AIAA New York office for six months; thereafter, photoprint copies are available at photocopy prices from AIAA Library, 750 3rd Avenue, New York, New York 10017

15

A SPACE MAINTAINABILITY EXPERIMENT ABOARD THE BEN FRANKLIN SUBMERSIBLE DURING THE 30-DAY GULF STREAM DRIFT MISSION

John R. Kappler
Maintainability Engineer
Grumman Aerospace Corporation
Bethpage, New York

and

Chester B. May
Submersible Crewmember and Experiment Director
Life Sciences Engineer
NASA, MSFC, Huntsville, Alabama

Abstract

In the summer of 1969, a deep submersible drifted for 30 days below the surface of the Gulf Stream, while operated by a six man crew. Although the main purpose of the mission was oceanographic research, the crew's activities and completely self-contained environment resembled those of a space station such as Skylab.

Because of these similarities, NASA funded a Space Maintainability experiment to investigate onboard vehicle maintenance during the actual conduct of a scientific mission.

I. Introduction

The opportunity to study maintenance of a complex system in a dynamic situation under total isolation for a long mission is quite rare. Laboratory tests have provided useful information but have always been conducted under static conditions with help from outside the tank or test chamber.

The Gulf Stream Drift Mission was the maiden voyage of the BEN FRANKLIN and the major scientific objectives of this mission provided a sense of motivation for the crew which placed maintenance into proper perspective with relation to operation of the entire vehicle.

The 30-day mission was conceived by Dr. Jacques Piccard in 1965 as a means for exploring the Gulf Stream from Florida to Nova Scotia using visual observations, bottom photography, biological surveys, and acoustical surveys. In 1967 the Grumman Corporation agreed to undertake and finance the mission and establish a program for the design, development, and construction of the BEN FRANKLIN – a deep submersible capable of oceanographic research with a crew of six for missions of 30 days or more without surfacing. The vessel has a self-contained life support system as well as propulsion, stabilization, power, communication, and experiment subsystems. It resembles a space station, such as the Skylab, in size and shape. See Fig. 1 and 2.

The Naval Oceanographic Office (NAVOCEANO) provided a surface support vessel and two BEN FRANKLIN crewmembers to perform ocean experiments. The remainder of the crew of six consisted of two pilots (including Dr. Piccard), a relief pilot oceanographer, and a NASA crewmember responsible for the NASA space-oriented studies.

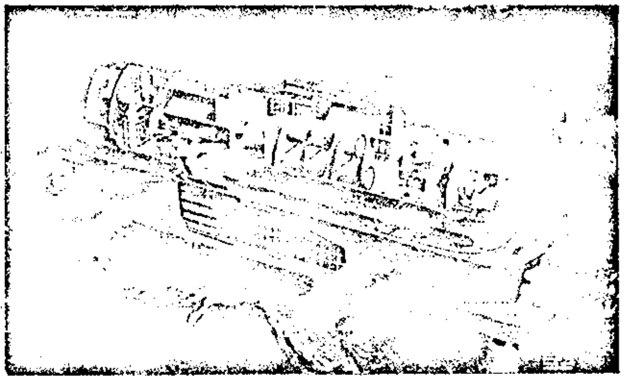
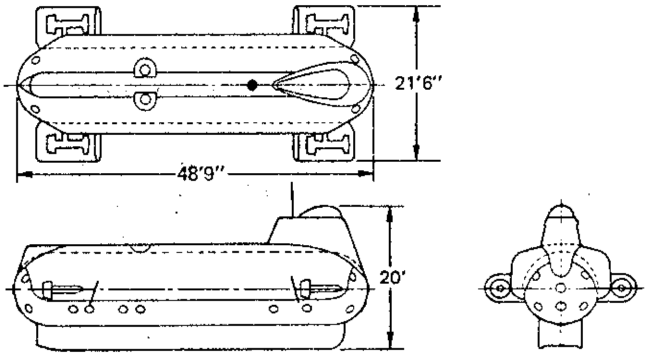


Fig. 1 Cutaway View of BEN FRANKLIN

The mission began on 15 July 1969 when the BEN FRANKLIN submerged into the Gulf Stream off West Palm Beach, Florida. It terminated 30 days, 11 hours later when the BEN FRANKLIN surfaced 360 miles south of Nova Scotia. The drift covered 1444 n mi at an average depth of 650 ft. Ten excursions were made to depths between 1200 and 1800 ft.



DISPLACEMENT	130 TONS
OPERATIONAL DEPTH	2000 FT
COLLAPSE DEPTH	4000 FT
MAX SUBMERGED SPEED	4 KT
LIFE SUPPORT	6 MEN FOR 6 WK
PAYLOAD	5 TONS
TOTAL POWER	756 KWH
VIEWPORTS	29

Fig. 2 BEN FRANKLIN Characteristics

II. Objectives of the Space Maintainability Experiment

The intent of the experiment was to obtain an insight into onboard maintenance performed in confined/isolated environment and to apply this insight into planning for maintainability in future space vehicle design and missions.(1, 2) The following specific objectives were established for the experiment:

- Evaluate the impact of Maintainability on mission success
- Evaluate the effectiveness of current aircraft maintainability analysis and prediction techniques on a space-type mission
- Determine the maintenance workload expended during the mission
- Determine the maintenance workload distribution
- Determine the differences, if any, between maintenance performed in a stressed vs an unstressed environment
- Investigate the effects of training, learning, skills, spares, tools, test equipment and onboard technical information on maintenance performed during the mission

III. Experiment Approach

The maintainability study was accomplished in six distinct phases:

I Developed experiment plan

II Analyzed onboard systems and equipment to determine preventive and corrective maintenance requirements – (maintenance frequencies, potential failures, tasks, etc.)

III Defined experiment tasks, completed M predictions, prepared for spares, tools, log books, procedures, training, etc. and assigned maintenance tasks to various crew

IV Trained crew and conducted dockside time trials of maintenance actions to obtain baseline data for comparison with mission performance

V Recorded actual performance during mission via written reports, log entries, photographs, movies, and tape recorders

VI Debriefed crew, reduced and analyzed data and wrote final report(3)

Experiment Plan - Phase I

All of the major study task elements were identified and inserted into a block diagram to assure that the flow of events and data would meet the mission calendar milestones and provide meaningful results.

Maintainability Analysis - Phase II

The BEN FRANKLIN is equipped with numerous complex subsystems (see Table 1) but there were only three months available for the maintainability analysis, writing procedures, making check lists, forms, and estimates prior to start of the mission. Therefore, only the most promising candidates were selected for this experiment based on:

- Scheduled maintenance requirements
- Unscheduled maintenance requirements
- Availability of detailed design information
- Similarity to space type of equipment
- Accessibility to the crew

TABLE 1 SYSTEMS ONBOARD BEN FRANKLIN

- MAIN BALLAST TANK SYSTEM
- EXTERNAL BLOW SYSTEM
- SALT WATER SENSORS SYSTEM
- VARIABLE BALLAST SYSTEM
- SHOT BALLAST SYSTEM
- EMERGENCY SHOT BALLAST SYSTEM
- HIGH PRESSURE PNEUMATIC SYSTEM
- SAS RELEASE SYSTEM
- HYDRAULIC PRESSURE SYSTEM
- ENVIRONMENTAL CONTROL SYSTEMS
- LIFE SUPPORT SYSTEMS
- EXTERIOR LIGHTING SYSTEMS
- INTERIOR LIGHTING SYSTEMS
- OCEANOGRAPHY RESEARCH EQUIPMENT
- PILOT'S CONTROLS AND CONSOLE
- ELECTRICAL POWER AND DISTRIBUTION SYSTEM
- MAIN PROPULSION SYSTEM
- ATTITUDE CONTROL AND STEERING SYSTEM
- CAUTION AND WARNING INSTRUMENTATION
- FLIGHT INSTRUMENTATION
- RADIO AND INTERCOM SYSTEM
- UNDERWATER TELEPHONE SYSTEM
- CTFM SONAR SYSTEM
- FATHOMETER, PINGER, DEPTH SENSORS – GAUGES AND RECORDING SYSTEMS
- PERISCOPE AND UNDERWATER TV SYSTEMS
- DAMAGE CONTROL AND EMERGENCY SYSTEMS
- MICROBIOLOGY RESEARCH EQUIPMENT
- PSYCHOLOGY AND PHYSIOLOGY RESEARCH EQUIPMENT

Experiment Task Definit

Twenty-seven independent maintenance tasks (13 scheduled and 14 unscheduled) were finally selected as the core of the experiment.

The scheduled tasks were chosen because they...

... were essential to safety and operation of the vessel:

- Hull penetrator inspection
- Sea valve inspection and operational check
- Hydraulic system inspection
- Pneumatic system inspection
- Fathometer inspection and service

... involved testing and monitoring for degradation and failure in the critical power and propulsion systems:

- Battery voltage monitoring and hull resistance check
- Ampere-hour system check for power consumption. (The procedure for this task included system calibration and repair instruction, plus an alternate power saving mode of operation)
- Hull resistance check of main propulsion and rotational motors

... typified a fairly simple routine job:

- NASA tape recorder inspection and service

... involved one of the more critical areas for long-duration space missions, "bacteria and microbial contamination control":

- Bacteria filter element replacement (water system)
- Water system potability test
- Microbial contamination tests for interior air, surfaces, and personnel

It was anticipated that learning curve effects would be observed from repetitive observations of routine type scheduled maintenance actions.

The 14 unscheduled maintenance tasks represented emergency repairs. Some were designed to prevent degradation and malfunction of equipment, while others were necessary to prevent catastrophic consequences and possible mission abort. These tasks were:

- Fuse troubleshooting and replacement
- Underwater telephone repair
- Macerator repair
- Water pump repair
- Gas chromatograph service and repair
- Camera service and repair
- Foreman experiment service and repair
- Egan experiment repair
- Crew performance tester repair
- Oxygen regulator repair
- Battery cell string jumping
- Hydraulic and pneumatic valve repair
- Odor removal blower repair
- Cold water sterilization

The equipment affected by each selected (controlled) maintenance action was analyzed in detail to provide all of the scheduled maintenance requirements, as well as the major failure modes most likely to be encountered during the 30-day mission. This involved review of all available equipment and installation drawings, schematics, manuals, and handbooks as well as contact with vendors, installation engineers, crew members, and equipment both on and off the vehicle.

A workbook was developed for use during the mission. The book included:

- Detailed maintenance procedures
- Special charts to show locations of fuse boxes, terminal parts, test points, etc.
- Check lists for scheduled maintenance
- Calculation sheets for tasks such as power consumption, drive motor lead hull resistance, battery lead hull resistance, etc.
- Data sheets to record elapsed times and essential performance and maintainability data for all maintenance actions (scheduled and unscheduled, controlled and uncontrolled). The NASA Maintainability Engineer used a stop watch to record elapsed times
- Special incremental task element recording formats for easy comparison of results with Method II and III predictions

A Maintainability Analysis was performed and an MTTR was predicted for each maintenance procedure in the experiment using Methods II and III of MIL-HDBK-472.(4) As a result of the analysis, recommendations were made for spares, tools, and test equipment to support the vehicle during the mission. However, as in a spacecraft, space on the BEN FRANKLIN was at a premium and the spare parts, tools, and technical information taken aboard were limited to a selected list based on experience and functional priority or criticality of the affected equipment.

Crew Training and Dockside Time Trials - Phase IV

The entire six-man crew was given the opportunity to review and comment on the content of the NASA Maintainability Experiment. In particular the NASA Engineer, the BEN FRANKLIN Captain, and the Pilot were given a special briefing and familiarization with the content and details of the maintenance procedures, check lists, charts, data sheets, spares, and tools for the experiment.

Dockside time trials and demonstrations were performed on the vehicle by crewmembers and other qualified personnel to establish baseline data, and to be certain that all maintenance procedures were fully understood. All scheduled maintenance tasks were exercised except for those parts requiring disassembly of equipment. Similarly, all of the unscheduled maintenance repair tasks had to be checked by simulation exercises.

Mission and Performance Data Recording - Phase V

This phase covered all of the data taking and recording of maintenance actions accomplished by the crew during the 30-day mission. To help in the mission data analysis, the crewmembers were identified with their specialties and assignments as indicated in Table 2.

TABLE 2 CREWMEMBER ASSIGNMENTS

CREWMEMBER ASSIGNMENT/BACKGROUND	FUNCTION PRIMARY/SECONDARY
MISSION LEADER/SCIENTIST	SCIENTIFIC/OPERATIONS
OCEANOGRAPHER/OCEANOGRAPHY	SCIENTIFIC/NONE
PILOT/NAVAL ENGRG	OPERATIONS/SCIENTIFIC
OCEANOGRAPHER/ELECT. ENGRG	SCIENTIFIC/MAINTENANCE
PILOT/NAVAL ENGRG	OPERATIONS/MAINTENANCE
TEST ENGINEER/ENGINEERING	MAINTENANCE/SCIENTIFIC

Crew Debriefing, Data Reduction and Analysis - Phase VI

The crew was debriefed at Grumman, Bethpage, directly after the mission to ascertain additional details, rationale, and background information in connection with various maintenance actions as recorded in log books and data sheets. Following this, data reduction and analysis of all the feedback data was accomplished.

Although the NASA Representative was available for only about 50% of each day, most of the maintenance performed on the controlled equipment was timed and recorded.

The debriefing interviews, detailed log investigations, review of NASA's stop-action films, and personal meetings with each crewmember resulted in positive identification of 1355 unreported maintenance actions and determination of the manpower expended in these tasks.

All the reported and unreported tasks were compiled into a Maintenance Action Summary which lists the number of times each task was performed, and the elapsed times required. See Fig. 3 for overall task breakdown.

	NO. TASKS	NO. ACTIONS	MMH
• CONTROLLED MAINTENANCE			
– SCHEDULED	14	1048	78.2
– UNSCHEDULED	3	13	4.2
SUBTOTAL	17	1061	82.4
• UNCONTROLLED MAINTENANCE			
– SCHEDULED	11	264	190.0
– UNSCHEDULED	26	30	49.3
SUBTOTAL	37	294	239.3
TOTAL	54	1355*	321.7

*321 ELECTRONIC, 1034 MECHANICAL

Fig. 3 Breakdown of Maintenance Workload

IV. Manpower Distribution

Using the Maintenance Action Summary (Table 3) two useful plots of manpower distribution were developed: Scheduled and unscheduled maintenance performed during each mission day (Fig. 4), and cumulative daily mission maintenance workload (Fig. 5). Of the cumulative total, scheduled maintenance took 268.2 man-hours, and unscheduled maintenance took 53.5 man-hours. The total maintenance workload averaged 10.7 man-hours per day.

Scheduled Maintenance

A minimum of 6 man-hours per day was spent on routine scheduled maintenance. The cyclic nature of the scheduled maintenance workload added as much as 8 to 9 man-hours every third day. During the first 11 days, this cyclic workload was very heavy indicating that the crew may have been very conscientious. They devoted more time to scheduled maintenance on days 2, 5, and 11 when the BEN FRANKLIN was drifting at 600 feet in the Gulf Stream.

On days 13 through 17, the crew attempted to distribute the scheduled maintenance work-load more evenly over this 3-day cycle. From day 18 to the end of the mission, the fluctuation in scheduled maintenance was reduced to a point satisfactory to the crew.

Deep dives were also observed to have an effect on the amount of maintenance performed on any given mission day. During the early part of the mission, the daily maintenance workload was reduced on deep dive days to accommodate the increased operational workload. The days immediately preceding and following each dive were generally heavy maintenance days. As their experience with the dive maneuvers increased, the tendency to reschedule maintenance became less noticeable.

From day 16 through 26, the amount of daily scheduled maintenance activity was at a low level corresponding to a generally overall lower level of activity, especially in the oceanography area. The crew was also able to improve on the scheduled maintenance workload by combining tasks and better organizing their efforts.

Unscheduled Maintenance

In general there was a high level of unscheduled maintenance activity during the first-half of the mission, as compared with the last-half. During the first-half, the crew spent about 2 man-hours per day on unscheduled maintenance. During the drift periods (when not diving or ascending) very little unscheduled maintenance was accomplished, except for two major unscheduled repair actions. These complex repairs were deferred until there was an opportunity to devote a long uninterrupted segment of time to perform the work properly.

These observations of the maintenance workload gave an insight into the flexibility and resourcefulness of the crew. They were able to organize, modify, and adjust this workload, not only to suit operating conditions, but also to take advantage of their experience gained during the mission.

V. Total Maintenance Workload vs Total Manpower Available

Figure 6 shows some significant maintenance workload trends. The maintenance workload varied from 12% to 31% of the total manpower available during any one day. The total maintenance workload was 17.3% of the total on-duty manpower available. This was the equivalent of one man devoted to maintenance full time.

At the beginning of the mission, the 3-day average workload value was approximately 20%, and gradually decreased to 14% at the end of the mission. This was the result of improved operations by the crew, decreased requirements for equipment service and repair, and postponement of the following maintenance repairs to the end of mission:

• Macerator Motor Switch	Not critical
• Light Experiment	Not critical
• CO_2 Gage	Not critical
• B-2 Ampere-Hour Counter	Not critical

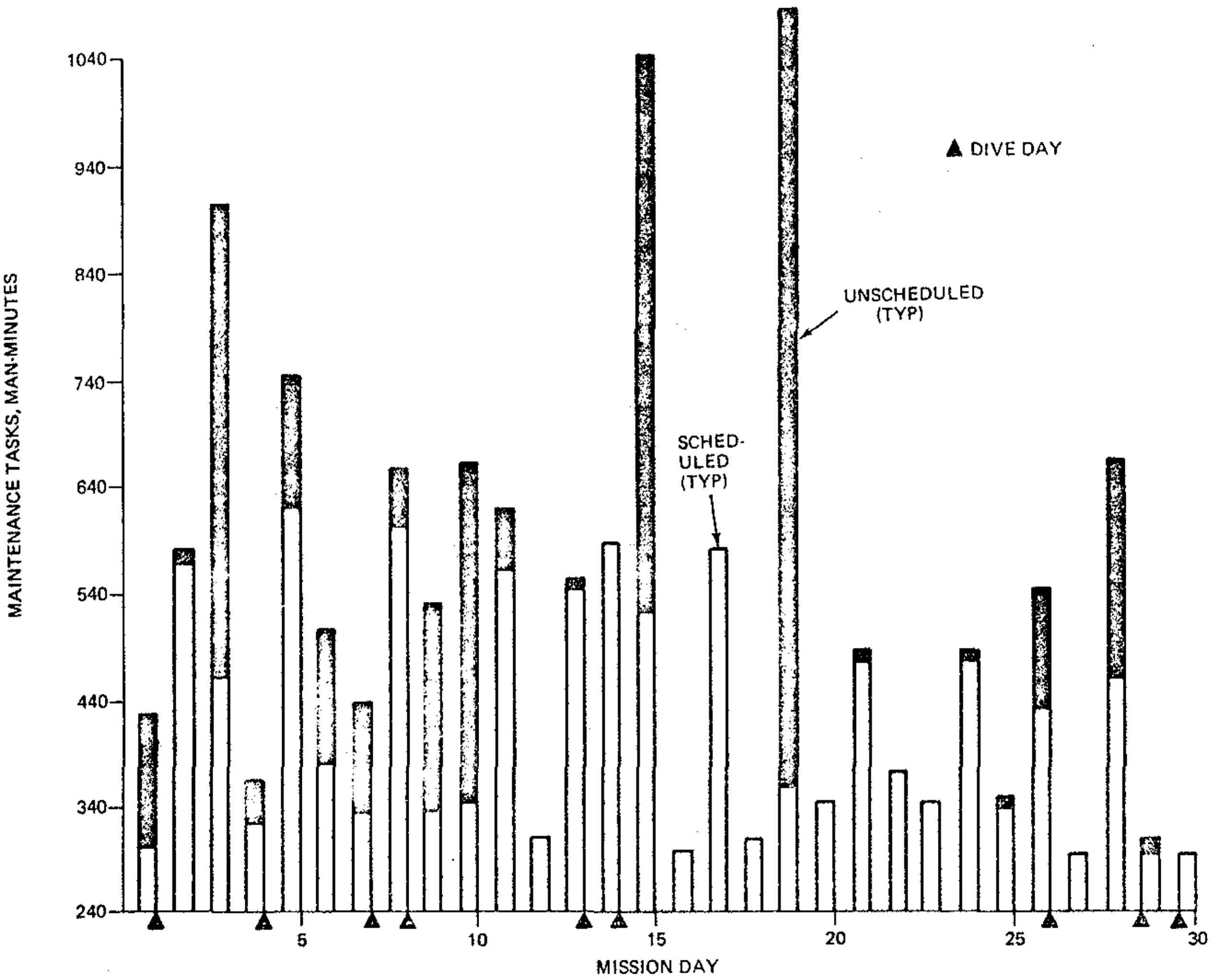


Fig. 4 Manpower Distribution By Day

There was an obvious stabilization of the maintenance workload and, if the mission had continued beyond 30 days, scheduled maintenance would have leveled off at approximately 10%, or 6.36 man-hours per day, based on the trend established during the last 15 mission days plus the unscheduled maintenance.

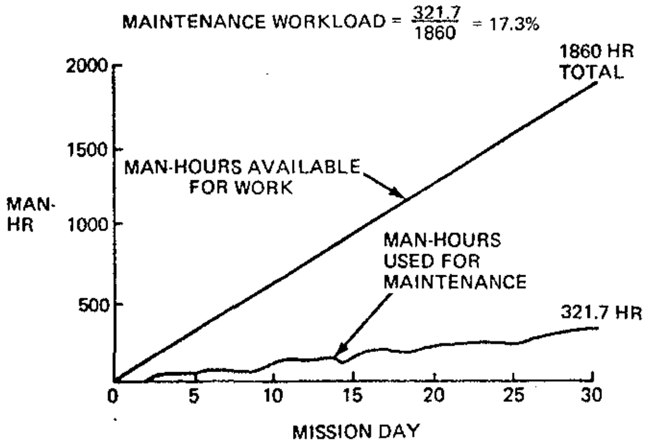


Fig. 5 Cumulative Maintenance Workload

Unscheduled maintenance repairs absorbed 2.87% of the total available crew duty time. This was reasonable considering the complexity and type of equipment aboard.

The failure of the macerator switch would have become mission critical if it had occurred earlier than day 29. It caused the loss of the macerator electric sewage disposal function which was backed up by a manual pumping system.

The following seven items failed and could not be repaired because they were external to the vessel and Eva was not planned for this mission:

- Fathometer
- Sub-bottom Profiler
- Magnetomometer
- Ship's Compass
- Light Transmissometer
- Ocean Current Meter
- NAVOCEANO 70 mm Camera

VI. Crewmember Maintenance Workload Distribution

Figure 7 summarizes the maintenance work performed by each crewmember on a daily basis. Figure

8 indicates each man's work effort as a percentage of the scheduled, unscheduled, and total maintenance performed during the mission. As computed from Fig. 7 crewmembers 2, 4, and 6 performed 86.8% of all mission maintenance. These same three men performed 84.1% of the scheduled maintenance, while only two of them (4 and 6) performed 96% of all the unscheduled maintenance.

VII. Maintenance Task Analysis

This portion of the data analysis deals with the subjective aspects of maintenance performed during this GSDM.

When a maintenance task or action is analyzed, those aspects relating to physical design accessibility, tool requirements, safety, spares and test equipment become quite obvious. There are many things a maintenance man brings to the job such as: skill, experience, training and knowledge of the task, ability to use technical information, and resourcefulness or ability to improvise. All of these factors are, in turn, affected by the working environment.

The maintenance man's efficiency is influenced by environmental factors, such as noise, stress, lighting, tight quarters, temperature, and humidity. His mental attitude also has an effect, especially in the areas of motivation and boredom. All of these factors are inherent in every maintenance action. Admittedly, some are difficult to measure, but their influence can affect the amount of time required to perform any given maintenance task. In the following discussion, an attempt is made to relate these factors to the performance of maintenance aboard the BEN FRANKLIN.

Skills

One of the most significant factors affecting the successful completion of the mission was the cross section of technical skills in the crew. Various maintenance tasks were ranked in order of difficulty vs the crewmembers who performed each task. There was an obvious relationship between technical skill levels observed and the difficulty of the maintenance tasks performed by the various crewmembers. During scheduled maintenance, the workload was generally shared by most of the crew. However, when an unscheduled maintenance task appeared, it was almost always performed by one of two crewmembers. This fact suggests that these two men were confident enough in their abilities to assume this burden in order to insure a higher level of mission success. The factors which instill this level of confidence are heavily influenced by the attitude of the individual and his general background of experience.

Crewmembers 4 and 6 performed all of the difficult tasks and most of the moderately difficult tasks, crewmembers 3 and 5 performed the remainder of the unscheduled maintenance.

The highly skilled technician (4) repaired complex electronic equipment despite the lack of technical information. This was accomplished by detailed tracing of circuits which required a thorough understanding of the general theory and operation of the various types of equipment involved. When a failure in one circuit induced a secondary failure in a high priority experiment circuit, he rewired the circuits, switched several functions around, and substituted parts into the original high-priority circuit so that the equipment was put back

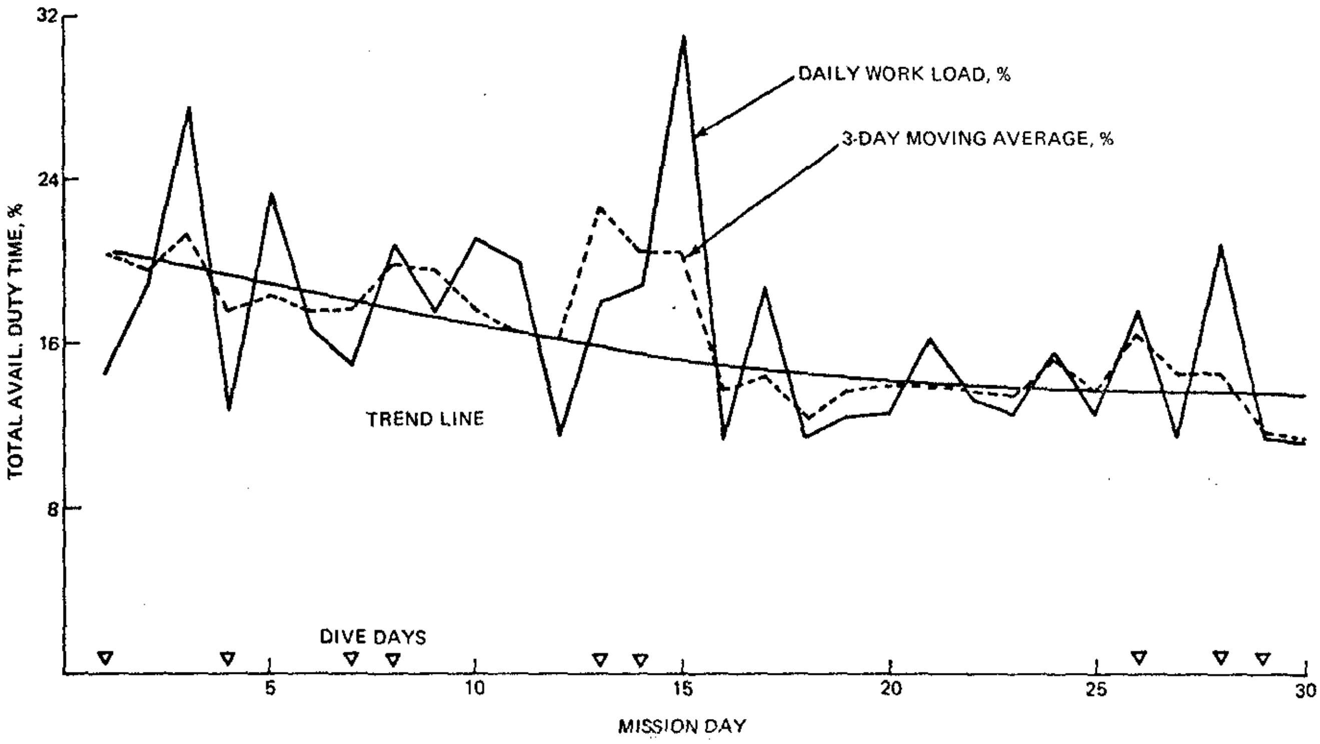


Fig. 6 Percent of Total Available Working Hours per Day Consumed by Maintenance

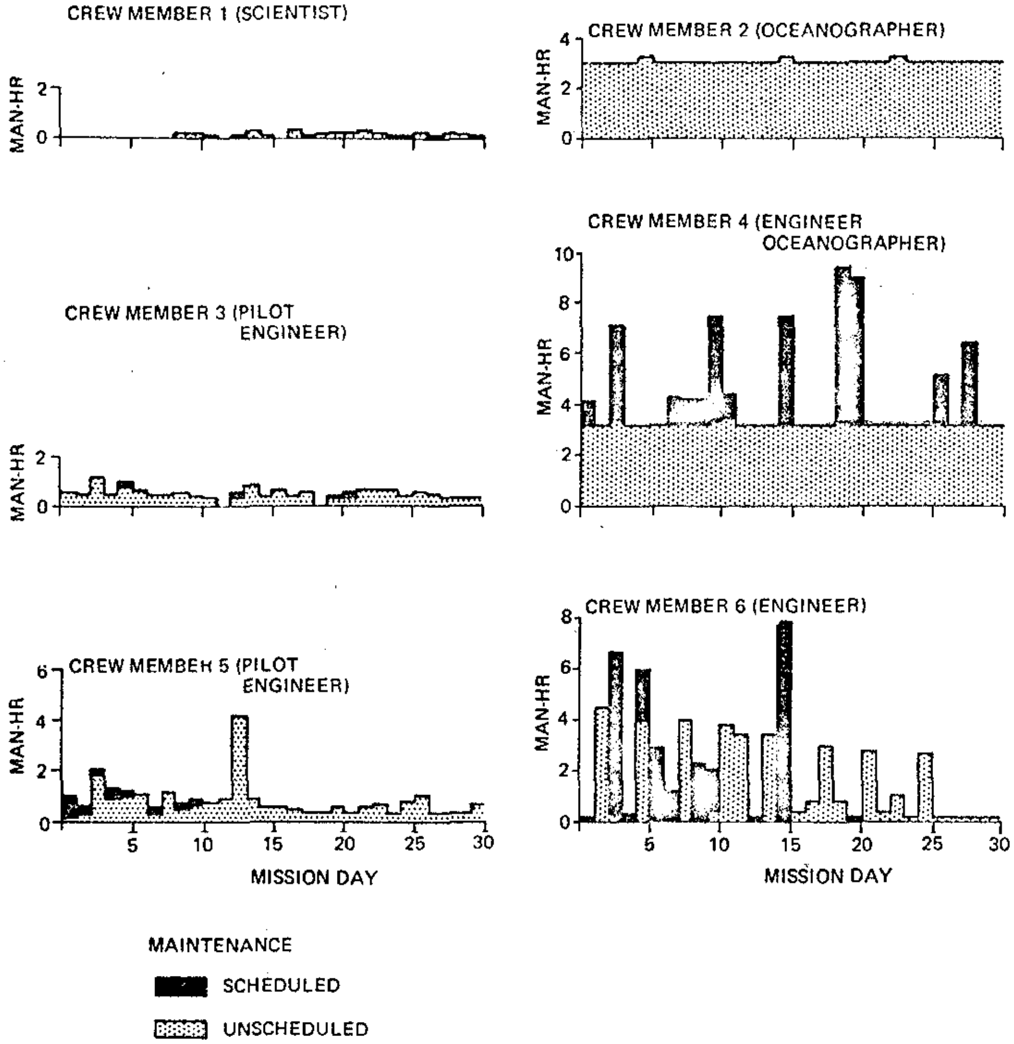


Fig. 7 Crew Member Maintenance Workload Profiles

in operation. Motivation was an important factor in accomplishing these tasks; however, skill was the most important ingredient.

Learning and Performance

Tasks which resulted in slow learning were generally those in which there were several interrelated steps that involved a high degree of organization, such as setting-up a large number of Agar plates for the Anderson Air Sampler. In this case, repeated performance of the task led to the development of a method which saved time.

When a high level of organization was not required, improvement in the time to perform the task was not noted, indicating a fast level of learning prior to the mission.

To get a better insight into the effects of learning on repetitive maintenance tasks, the scheduled maintenance data were analyzed. The percent learning associated with each task was defined by the following equation (5):

$$\% \text{ Learning} = \left(1 - \left[\frac{\text{Log}\,\frac{T_1}{T_N}}{\text{Log}\ N}\right]\right) \times 100$$

where:

T_1 = First value of repair time

N = Number of times repair is performed

T_N = Cumulative average time over the N repetitions

Tasks in which fast learning was noted were set in procedure and did not require decision making. One such task required connecting a megohm tester between a terminal point and ground. The value of the resistance was then recorded. The 24 electrical terminals were located in four junction boxes. The 6 terminals in each box were reached by removing the box cover and repeating the procedure for each box. Once the location of the terminals and boxes were known and the megohm test became routine, there was little possibility of improving the maintenance time.

BLACK BOX REMOVAL

GAINING ACCESS TO INTERIOR OF BLACK BOX FOR REPAIR

Fig. 8 System Level Maintenance

Tasks which took longer to learn required a high level of proficiency and unique decisions were made each time they were performed. One of these tasks consisted of selecting biological samples from the interior surfaces of the vessel and then analyzing them for a bacterial count. The analysis was unique to each sample; therefore, little learning could be accomplished, except after a great deal of experience.

The replacement of the water system bacterial filters required exceptional care to prevent contamination, and a system for accomplishing the task had to be developed. This produced a slow-learning cycle.

It is apparent that to effectively use the available manpower for scheduled maintenance aboard a space-type vehicle, step-by-step detailed maintenance procedures must be designed for quick and easy performance, with minimum demands for extensive and complex tasks.

Training

The training aspect of the experiment had a significant effect on the performance of maintenance during the course of the mission. It was essential to the mission that the crew be thoroughly familiar with the general operation of the vehicle's systems. They also had to be familiar with the specific troubleshooting and repair procedures, prepared as part of the NASA Maintainability Experiment. This helped to relieve much of the anxiety in performing maintenance and produced crew confidence.

The procedures for scheduled and unscheduled maintenance gave confidence to the crew since they knew they did not have to rely on memory for any of the controlled maintenance tasks.

Because of the limited time available for crew training, specialization in specific maintenance tasks was necessary. This expedient limited the flexibility of individual crewmembers to perform other maintenance tasks.

Onboard Maintenance Provisioning

Providing the proper technical information, tools, spares, and test capability was an essential part of the total maintainability task. The ability to support the onboard maintenance function was amply demonstrated by the fact that the crew reported satisfaction with the spares, tools, and technical information supplied for the controlled maintenance tasks. The only provisioning weakness encountered during the mission was in the area of uncontrolled electronic equipment maintenance which was outside the scope of this experiment.

Working Conditions

The times recorded for microbial sampling tasks during the dockside time trials, were less than the values established during the mission. Considering the space required to set-up these tasks, the numerous pieces of equipment that must be handled, and the interference of these actions with the normal activity in the vessel, it became apparent that the limited space available imposed a penalty on the performance of these tasks. Work was performed on the wardroom table which was quite small considering the handling of many Petri dishes involved in these complex tasks. Since there was no other work area set aside for performing this work, every piece of equipment had to be broken down and returned to its storage area after the sampling was complete. This took longer than anticipated.

Similar effects were noted in the repair of electronic equipment. Repairs were made on removed equipment in various areas, such as the passageway, the bunks, and the aforementioned table. This did not lead to efficient repair operations.

Repetitive Tasks

One type of maintenance prediction in gross error with actual mission data was the inspection of the vessel systems. In general, a safety inspection was performed every 4 hours during the mission. This inspection included the vessel, penetrators, sea-valves, and the hydraulic and pneumatic systems. Generally speaking, these tasks became tedious since they were repetitive.

As a result, the different inspections were combined by the crew into one operation and in time became quite superficial in nature. This trend could be accounted for in two ways. First, as the performance of a system proved to be dependable, less attention was directed to it by the crew. Secondly, the importance of accomplishing these safety inspections in every detail obviously diminished with the passage of time.

The consequence of these trends was that the safety inspections which normally should take half an hour were condensed to 8 minutes. Better organization or integration of these similar inspection tasks should have been accomplished prior to the mission. This accounted for some of the time differential. An important element inherent in the final reduction of inspection time was the diminishing importance the crew attached to the task details as the mission progressed. Therefore, if there were good reasons for repetitive safety type inspections, then priorities should have been established and the crew indoctrinated with the importance of these details.

Maintenance Levels

Figures 8 through 11 illustrate the performance of maintenance tasks aboard the BEN FRANKLIN which are directly analogous to maintenance levels that would be required on a long-duration space mission.

System level maintenance is shown in Fig. 8 (black box removal) and Fig. 9 (online system adjustment and system fault isolation by manual probing to determine the faulty module).

Bench level maintenance is illustrated in Fig. 10, which shows a faulty printed circuit board being removed and the failed parts (transistors) about to be replaced.

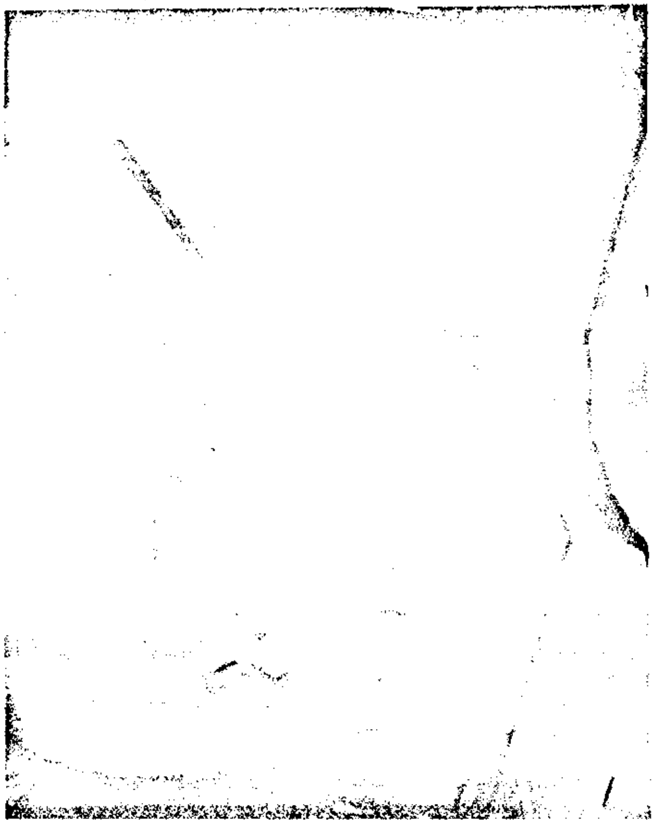
Visual inspection is shown in Fig. 11.

Prediction Technique Evaluation

The first consideration in the numerical analysis was to identify the correlation between each estimating technique and the actual data. As a result of the correlation, it was then possible to evaluate each technique with respect to qualitative and quantitative accuracy.

Dockside time trials were compared with the actual mission data to determine the performance of maintenance in a controlled unstressed environment as compared with that encountered during the GSDM.

To aid in the statistical analysis of the mission data, multiple linear regression equations were developed for each of four sets of data:



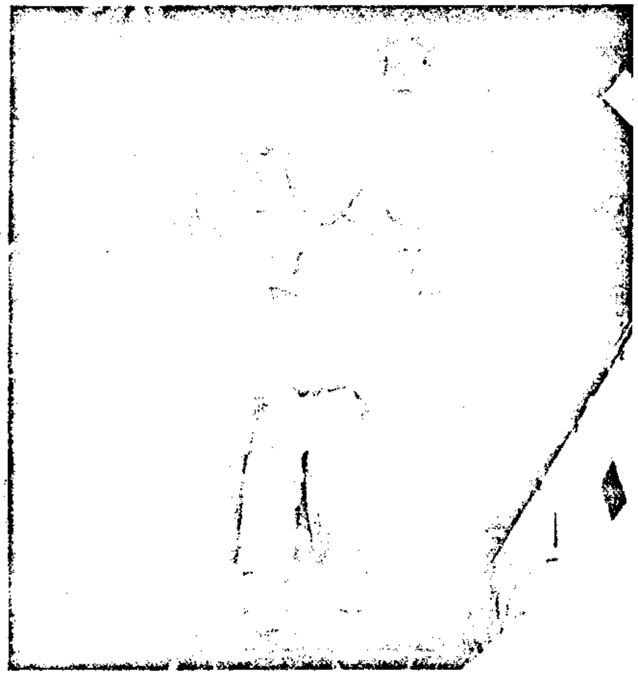
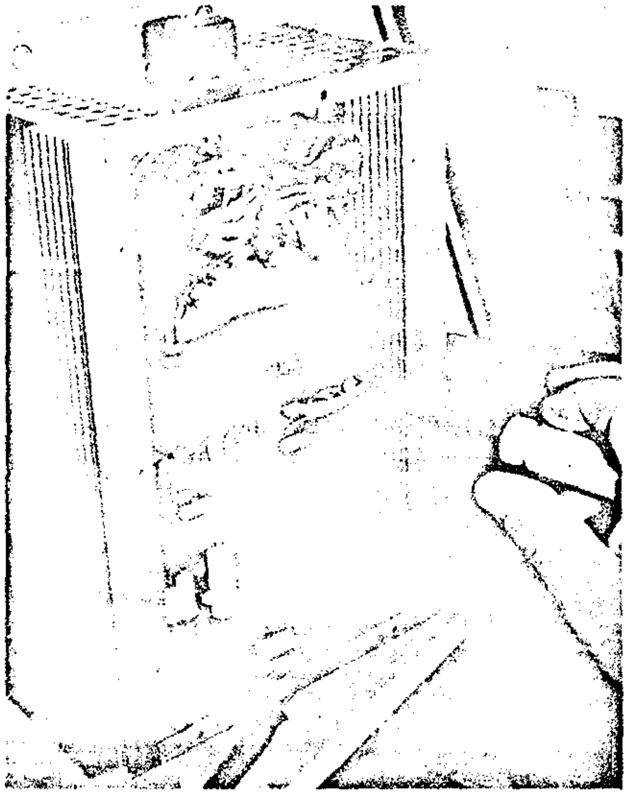


Fig. 9 System Level Adjustment and Fault Isolation

- Methods II and III (MIL-HDBK-472) predictions vs actual data
- Dockside task performance trials vs actual data
- Control case of Method II (Aircraft Program) predictions vs early operational data from that aircraft program. This provided a means of measuring the repeatability of the Method II prediction technique



BLACK BOX REPAIR BY REPLACEMENT OF SUBASSEMBLY

SUBASSEMBLY (PCB) REMOVAL AND READY FOR PART (TRANSISTOR) REPLACEMENT

Fig. 10 Bench Level Maintenance

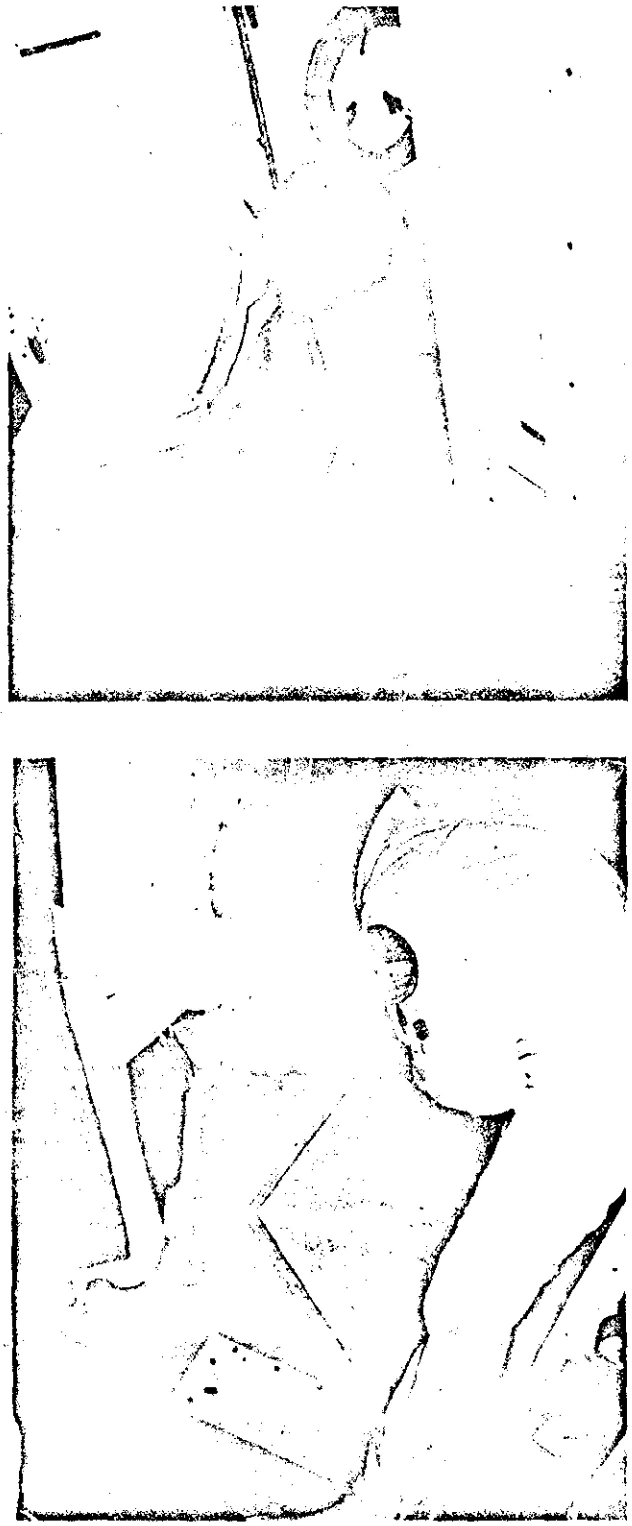


Fig. 11 Typical Scheduled Maintenance Tasks, Inspection of Head and Power Distribution System

Method II Prediction Analysis. The results of the multiple regression analysis for the correlation between Method II estimates and actual mission data are shown in Fig. 12.

The reduction of Method II predictions shows that estimates were generally conservative for any

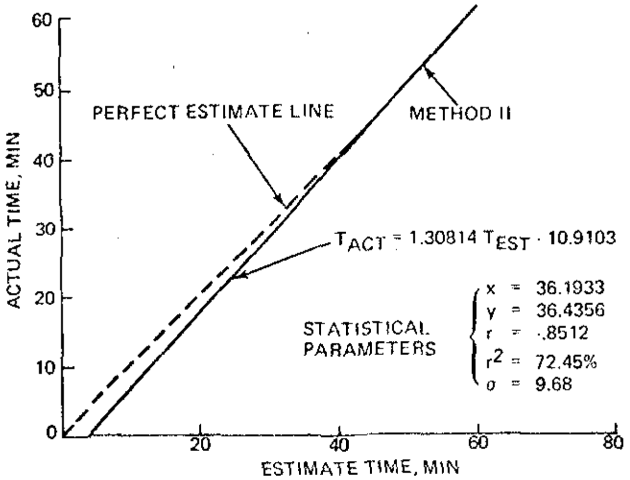


Fig. 12 Actual vs Method II Task Time Analysis

estimate up to 35 minutes. The slope of the regression line is almost in line with the line of perfect prediction, indicating that little if any correction factor is required to adjust time estimate to real values. There is a bias in our predictions of about 8 minutes which if added to the predicted values would result in realistic estimates of actual times to perform required tasks.

The next consideration was to evaluate the quality of the regression line in Fig. 12. The standard deviation was 9.68 minutes, indicating a poor fit, but this error is relative to the population size and would have been smaller with a much larger number of data points. The next parameter was the correlation coefficient r which cannot be greater than +1 or be less than -1. A value of +1 denotes perfect functional relationship between y and x. An increasing x associated with an increasing y, where r = -1, would again be a perfect functional relationship, but with x inversely associated with y. When r = 0, there is no relationship between x and y.

The Method II correlation coefficient r resulted in a value of .85, indicating a high degree of direct correlation between the predicted values and the actual values.

Another measure of quality in regression analysis *is the value of the coefficient of determination* (r^2). This parameter expresses the percent of confidence in the data, with ($1 - r^2$) as the percent that can be explained due to accidental randomness in the data points. The value for (r^2) was 72.45% which also indicated that our Method II relationships with actual mission data were not random in nature. The resulting overall assessment of the Method II technique indicated a generally reliable means of predicting overall maintenance task time with some inaccuracies, particularly on items that required short repair times.

Method III Prediction Analysis. The previously described procedure was repeated for the analysis of Method III data; the results of this analysis are shown in Fig. 13.

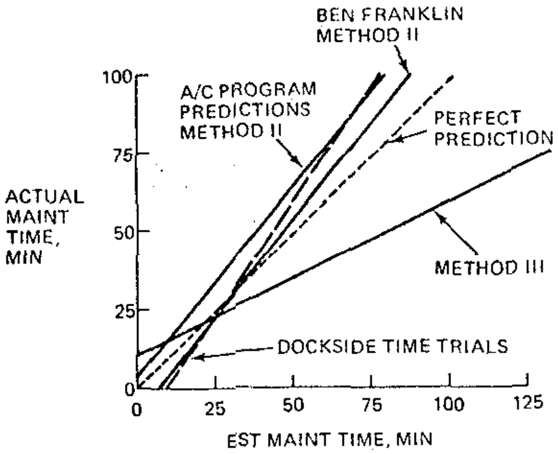


Fig. 13 Evaluation of Predictions vs Actuals

The regression line equation showed the existence of a very poor correlation between the predicted value of Method III and the actual data. The mean standard deviation was twice the standard deviation of Method II, and the degree of correlation was correspondingly very low. Clearly, Method II provided a much better tool for predicting maintenance task times.

Dockside Time Trials. This analysis was developed to define the relationship between the dockside time trials and the actual data. The result of the correlation analysis is shown in Fig. 13. The correlation coefficient for dockside time trial was not quite as good as Method II (r = 0.85 as compared to r = 0.94) but the standard deviation value (0) for dockside trial was much smaller than Method II predictions. *This indicated that the actual task times were relatively close to the dockside time trials.*

Generally speaking, for all tasks requiring less than 25 minutes, there seemed to be a learning effect which demonstrated itself in shorter actual task times.

In the case of those tasks which required maintenance times greater than 25 minutes, there were complications which were introduced during the course of the mission. These complications tended to increase the amount of time required to perform these tasks under mission conditions. Those tasks requiring *more than half an hour were generally complex* (most of them were scheduled maintenance procedures).

It can also be concluded that some aspects of the crew confinement added complications to the performance of these tasks. Some of these factors were: stress, lack of complete proficiency in performing certain difficult tasks, lack of adequate spare parts and equipment, and, finally, a desire not to create a disturbance while the rest of the crew was sleeping. This experiment was not geared to detect these sensitive causal factors.

There was no clear cut indication that the stresses had any discernible effect on the performance of various maintenance actions. This does not mean that there was no delta for stressed vs unstressed environment, but rather that there were no serious or critical equipment failures that required maintenance under severe adverse conditions. An extension of the mission may have brought such conditions into focus.

Method II Prediction Comparisons. The Method II predictions were found to be best in predicting the actual maintenance task times. To determine whether the results of this mission were truly representative of Method II prediction techniques, a control was established. This control consisted of a correlation analysis of early maintenance data for a modern aircraft program and Method II predictions for the same aircraft program. A comparison of the correlation analysis of the BEN FRANKLIN Method II predictions and the correlation analysis of this aircraft program predictions was made (see Fig. 13). The result of this comparison revealed that the slopes of the two regression equations were almost identical, i.e., very close agreement between the two programs.

The y intercepts of each curve highlight the differences between the two programs. In the case of the aircraft program, the regression equation y intercept indicated that the predictions generally underestimated the maintenance task times. This might be expected from early feedback data where technicians are cautiously performing maintenance actions on new equipment.

VIII. Conclusion

The NASA Maintainability Experiment had a rather significant effect on the outcome of the mission. By implementing the various phases of the experiment prior to launch, a number of maintenance problem areas were uncovered and appropriate solutions implemented. The experiment also redirected the project's thinking concerning spares, tools, training, and the need for onboard technical information. The program did have certain limitations which hampered the execution of the experiment. The experiment was conducted on a non-interference basis with the basic mission goals. The experiment was further restricted due to the limited amount of time available before the mission; however, all of the experiment objectives were either achieved or answered in part by the data returned from the mission.

The value of a dynamic test bed as an effective and early evaluator of spacecraft maintainability concepts has been verified by the results obtained from this experiment.

The amount of maintenance performed accounted for 17.3% of the total manpower available during the mission. This means that for this vessel and its complexity, approximately 1/6 of the crew's available time must be planned for maintenance activity. Of this maintenance workload, 74% was devoted to scheduled maintenance. Admittedly, spacecraft should not require as high a level of inspection and service work, however, the remaining 26% of the maintenance manpower was devoted to the critical unscheduled maintenance tasks upon which mission success depends. The skills and experience necessary to repair complex equipment must be present in the makeup of individuals selected for such a mission. It was apparent that training can aid in reducing the problem, but cannot altogether eliminate the need for maintenance skills and experience.

In making an accurate assessment of the anticipated maintenance workload during a space mission, prediction techniques such as MIL-HBK-472 Method II provide a suitable means by which these assessments can be made. The results of this mission indicate that onboard maintenance can be predicted with reasonable accuracy, but that further refinement through additional testing would permit more accurate assessment of individual tasks.

In summary, the significant conclusions resulting from the maintainability experiment were:

- Method II Maintainability Prediction Technique was the best approach for determining mission maintenance requirements
- A dynamic test bed provided valuable maintenance workload and performance data that can be used to define crew requirements for future missions in sealed isolated vehicles
- Maintainability support was essential to mission success
- There was no discernible difference in maintenance times performed under the range of mission stress conditions, compared to premission values
- The crew was resourceful in distributing the maintenance workload to suit varying mission conditions
- A maintenance corner or workshop area with a bench would have improved the efficiency and performance of certain offline equipment repairs and complex scheduled maintenance testing operations
- Measurement and control of bacteria was the most tedious and difficult job

TABLE 3 MAINTENANCE ACTION SUMMARY

DATE	MAINTENANCE TASK	NO. ACTIONS	COMPLETED	TASK TIME, MIN	REMARKS
VARIOUS	S BATTERY VOLT & RESIST TEST	6	X	15.9	
VARIOUS	S PENETRATOR INSP	240	X	*	*ACCOMPLISHED IN 8 MIN TOTAL TIME
VARIOUS	S SEA VALVE INSP.	240	X	*	
VARIOUS	S HYD. SYS. INSP.	240	X	*	
VARIOUS	S PNEU. SYS. INSP.	240	X	*	
VARIOUS	S FATHOMETER INSP.	6	X	5	
VARIOUS	S POWER COMSUMPTION CHECK	3	X	15	TERMINATED AFTER 10 DAYS
VARIOUS	S TAPE RECORDER SERVICING	30	X	1.5	
VARIOUS	S MEGGER CHECK PROPULSION SYS	5	X	24.3	
VAROIUS	S WATER SYS BACTERIAL FILTER REPLACEMENT	2	X	28.2	
VARIOUS	S WATER SYS PURITY TEST	9	X	56.6	
VARIOUS	S HUMAN FLORA TEST	9	X	111.7	
VARIOUS	S ANDERSON AIR SAMPLER	9	X	45.0	
VARIOUS	S RODAC SURFACE TEST	9	X	73.3	
VARIOUS	S AIR CONTAMINATION TEST	4	X	35.0	
VARIOUS	S GAS CHROMATOGRAPH TEST	2	X	113	
VARIOUS	S LiOH PANEL REPLACEMENT	11	X	16	
VARIOUS	S SILICA GEL REPLACEMENT	5	X	30	
VARIOUS	S DATA TAPE RECORDER SERVICE	30	X	5	DAILY CLEANING OF TAPE HEADS
VARIOUS	S POSITION DEPTH RECORDER SERVICE	30	X	5	DAILY CLEANING
8/3	S SHIP DEPTH RECORDER SERVICE	2	X	5	DAILY CLEANING
VARIOUS	U FUSE REPLACEMENT	10	X	8	
7/17	U MACERATOR MOTOR WIRING	1	X	220	
8/12	U MACERATOR MOTOR SWITCH	1		5	OCCURRED AT END OF MISSION–NOT MISSION CRITICAL
7/27	U EGAN EXPERIMENT	1			NOT MISSION CRITICAL
7/30	U STERILIZATION OF SURFACES		X		
7/14	U FATHOMETER FAILURE	1			EXTERNAL SENSORS
7/14	U SUB BOTTOM PROFILER FAILURE	1			EXTERNAL SENSOR
7/14	U MAGNETOMETER	1			
7/18	U SHIP COMPASS FAILURE	1			
7/14	U LIGHT TRANSMISSOMETER FAILURE	1			EXTERNAL SENSOR
7/30	U SLEEP MONITOR POWER DISRUPT	1	X	8	POWER DISCONNECTED TO REMOVE POWER FAILURE
8/2	U SLEEP MONITOR SENSOR FAILURE	1	X	210	
7/17	U COMMODE HANDLE REPAIR	1	X	8	
7/15	U AUX INVERTER FAN SERVICING	1	X	126	
7/29	U RELOCATION OF FLOOR COUNTER	1	X	48	REDESIGN OF SCIENTIFIC EXPERIMENT
7/17	U CLOGGED SHOWER SINK	1	X	4.2	
8/3	U CURRENT METER FAILURE	1		–	EXTERNAL SENSOR
7/17	U NAVOCEANO 70mm CAMERA	1		–	
8/11	U JAMMED TAPE RECORDER BEARING	1	X	107	
7/15	U HG PENETRATOR LEAK	3	X	–	
7/15	U AIR PRESSURE REGULATOR LEAK	1	X	–	
7/20	U PULSEMETER BATTERY RECHARGE	2	X	–	
7/15	U OIL LEAK SHALLOW DEPTH GAGE	1	X	–	
7/15	U CO_2 GAGE MALFUNCTION	1		–	NO SPARES

TABLE 3 MAINTENANCE ACTION SUMMARY (Cont)

DATE	MAINTENANCE TASK	NO. ACTIONS	COMPLETED	TASK TIME, MIN	REMARKS
7/16	U AMP-HR COUNTER FAILURE	1		–	NOT MISSION CRITICAL
8/1	U POSITION DEPTH RECORDER FAILURE	1	X	730	EXTENSIVE CANNIBALI-ZATION OF SPARE
7/19	U AFT TRIM PUMP SEIZURE	4	X	–	
7/14	U SIDE SCAN SONAR	1	X		OVERVOLTAGE CONDITION OF BATTERIES

DATE	MAINTENANCE TASK	NO. ACTIONS	COMPLETED	TASK TIME, MIN	REMARKS
VARIOUS	S NAVOCEANO CAL-IBRATIONS	50	X	*	* TOTAL CUMULATIVE TIME=180 HR.
VARIOUS	S NAVOCEANO SVCG EXP EQUIP	40	X	*	
VARIOUS	S NAVOCEANO OPER-ATIONAL M C/O	30	X	*	
VARIOUS	S NAVOCEANO EXP EQUIP. PREPARA-TION	30	X	*	
VARIOUS	S NAVOCEANO EXP DATA TAPE	30	X	*	

S = Scheduled Tasks   U = Unscheduled Task

References

(1) "System Effectiveness Through Interchangeability," B. Frumkin, AIAA 4th Annual Meeting and Technical Display, AIAA 67-984, Anaheim, California, October 23-27, 1967.

(2) "Redundancy vs Maintainability - Some Conclusions on the Crossover for Manned Missions," 2nd National Conference on Space Maintenance and EVA, Vol II.1.1, USAF Aero Propulsion Lab and NASA, Las Vegas, Nevada, August 6-8, 1968.

(3) "Use of the Ben Franklin as a Space Station Analog," Final Report No. 0512-70-8 Contract No. NAS 8-30172, Volume V, Maintainability, Grumman Aerospace Corporation, Authors: J. Kappler and R. Toussaint.

(4) MIL-HDBK-472, "Maintainability Predictions," DOD, 24 May 1966, Methods II and III.

(5) "Production Planning and Inventory Control," John F. Magee, McGraw Hill, New York, 1st edition, 1958.