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APOLLO EXPERIENCE REPORT - CONSUMABLES BUDGETING

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16. Abstract

In this report, the procedures and techniques used in predicting the consumables usage for the Apollo missions are discussed. Because of the many interfaces and influences on the consumables system, it is impractical to document all facets of consumables budgeting; therefore, information in this report is limited to the major contributions to the formulation of a consumables budget.

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SUMMARY

The consumables budgeting and predicting experience gained in the Apollo development missions and on the first lunar-landing mission are presented. The predicting experiences are limited to the propulsion, environmental, and electrical subsystems of the command and service module and the lunar module. Basic considerations pertaining to subsystem modeling and consumables prediction are presented with recommendations for advanced systems.

The development of simplified computer models that simulate the consumables systems has been proven to be an invaluable tool for use by the system engineer in the evaluation of the consumables budget. All the system requirements and constraints affecting the consumables predictions as well as the system procedures, the environment in which the subsystem will operate, the system-performance data, contingency and redline philosophy, crew procedures and modes of operation have to be identified for accurate predictions. Design considerations for advance systems should include better systems gaging, redundant-system performance modes that are similar to primary modes, the capability to transfer consumables that are mutually similar to different systems, and more conscientious documentation of performance data during system tests.

INTRODUCTION

The importance and need of subsystem consumable budgeting and analysis for mission planning were recognized early in the Apollo Program. For example, the earth orbital spacecraft development flights required a great deal of mission/system compatibility evaluation because systems designed for the lunar environment and operations had to be used and verified in the near-earth environment. Trajectory and attitude-maneuver techniques, sequences, procedures, and timelines affecting the consumables for all the Apollo missions had to be selected that met the test objectives within continually evolving system constraints. Adequate consumable margins had to exist for the nominal flight plan as well as for the alternate and contingency plans. In some cases, the consumables for the nominal plan were dependent on whether the mode of operation would be manual or automated or if the primary or the backup subsystem would be used. Also, the fact had to be considered that a particular subsystem consumable (for example, the reaction control system (RCS) propellant) had to be budgeted for three different modules, each of which had different requirements and constraints. Because of these and other factors, the task of predicting the consumable budgets for a lunar-landing mission was very complex.

The purpose of this report is to document how the consumables-budgeting task was accomplished for the Apollo electrical, environmental, and propulsion subsystems. The basic considerations for subsystem modeling and consumables predictions are presented together with the consumables-prediction experiences gained and significant problems experienced during the development flights and the first two lunar-landing missions. Recommendations for advanced systems are presented also.

DEFINITION OF TERMS

A consumables analysis is complete when every aspect of the usage is defined. Definition of this usage should be consistent for all consumables subsystems to allow the spacecraft manager to communicate in a common language with the mission-planning engineer and the spacecraft designer. The following items, which make up the budget, are used in this report in the context shown.

1. Loaded or capacity: The capacity is that quantity of consumables that is the nominal expected load. For batteries, it will represent the nominal expected ampere-hour rating.

2. Unavailable: That quantity of consumables that nominally cannot be considered for use in the mission plan is termed "unavailable." Unavailable consumables consist of the sum of defined nominal unusables, which are as follows.

   a. Trapped and otherwise unavailable consumables

   b. Outage resulting from a mean mixture-ratio imbalance

   c. Gaging, telemetry (TM), and real-time computational errors

3. Available for mission: That quantity of nominal-usage consumables remaining after the unavailable consumables are accounted for is termed "available for the mission."

4. Required for mission: That quantity of consumables that is needed in order to perform the nominal design or operational mission is termed "required for mission."

5. Nominal remaining: That quantity of consumables remaining after consideration of the unavailable and nominal mission performance requirements is termed "nominal remaining."

6. Dispersions: That quantity of consumables that involves consideration of the dependent and independent variables is called "dispersions." Some sources to be considered are variations in loading, flow rate, inert weight, system performance,

mixture ratio, flight parameters, and crew effect. Usually, sources are root sum squared; however, in some cases they may be considered as a separate bias.

7. Pad: The pad is that quantity of consumables remaining after all the previous considerations have been accounted for.

8. Contingencies: The contingencies are that quantity of consumables allotted for an operational philosophy with low probability of occurrence, or those events that must be budgeted to ensure successful recovery, or both types of events. Contingencies can be related to partial system failure or to flight-plan changes that will necessitate the use of additional consumables. All candidates for contingency allowance should be identified by subsystem and mission designers.

9. Outage: Propellant outage is that amount of fuel or oxidizer that remains when the other component is depleted. This amount of either fuel or oxidizer then is not available for maneuvers.

10. Margin: That quantity of consumables remaining after the highest probability of consumables usage has been accounted for is called the "margin."

BASIC CONSIDERATIONS

Some of the most interesting and difficult tasks and problems experienced in consumables budgeting occurred in the subsystem mathematical modeling of system-equivalent circuit or function simplifications and in the ability to identify all the requirements affecting the consumable predictions. This section presents the modeling requirements that evolved for the propulsion, environmental, and electrical subsystems and the basic considerations that affected the predicting ability of consumables analysts.

Subsystem Modeling

Usually, subsystem mathematical models used in digital programs for environmental, electrical, or propulsion system design are extremely detailed, cumbersome, and require long computer running times. These detailed design programs, however, can provide the consumables analyst with simplifying empirical data and analysis techniques to make the computer programs developed for consumables analyses smaller and more versatile. Correlation to flight data can also result in increased fidelity as the program progresses.

Proper evaluation of a system schematic or diagram of the system components or modules for its environment, proposed usage, and operational constraints usually resulted in further simplifications. An automated plotting capability also had to be implemented in the consumables-analysis programs so that plots of the predicted budget could be generated for documentation, crew charts, and flight-control plotboards.

Propulsion system. - The design of the propulsion-systems models is based on the propellant requirement for translation and rotation. The nominal mission profile can be computerized easily, given data regarding the series of burns to fulfill trajectory requirements and the proper spacecraft weight. The theoretical ideal rocket equation method of RCS propellant budgeting leaves much to be desired regarding the reliability of the data that are generated. Inexact information regarding jet-on times, tanked-propellant slosh, effects of rotating machinery, effects of center-of-gravity offset, effects of body-axis cross coupling, manual compared with automatic guidance, and the assumption of a rigid body all contribute adversely to actual propellant usage for a particular event.

Environmental control system. - The environmental control system (ECS) mathematical model is comprised of many different models. Atmospheric-revitalization, oxygen-supply, cabin-pressure, heat-transport, and water-management models must be integrated so that the interactions between these systems may be considered. A trajectory and attitude tape is used as input to the incident-heating routine. The cabin thermal model is used to calculate the cabin structural heat load. Electrical power system (EPS) heat loads are obtained as input from the electrical analysis. With this information, the program can predict the consumables usage history for water and metabolic oxygen.

Electrical power system. - Without an adequate model, an EPS analysis is done by simply summing the known loads, applying a fictitious power loss between the source (or sources) and the loads, and then subtracting the total energy that is required from the energy that is available. However, this is an inadequate method of monitoring the EPS of current and future spacecraft. Both the accuracy of the rate of energy consumption and, more importantly, the ability to observe the dynamic performance of the entire subsystem are lost completely without a computer representation of the electrical configuration. With a computer model, the consumables analyst has the ability to simulate electrical failures and generate data for malfunction identification and recognition. In addition, alternate steps can be planned in premission planning if real-time crises arise.

Several vital input parameters are needed to model an EPS subsystem adequately. The most important parameter or component to be modeled accurately is the energy source of the subsystem. Complete curves defining the voltage-current (V-I) characteristics of the source must be included for various operating-temperature ranges in the case of conventional power sources. For the case in which more than one source powers a spacecraft (for example, fuel cells and batteries), the interplay (load sharing) between the individual sources has to be modeled. Then, a complete representative power distribution network must be formulated. This network must be as accurate as possible to account realistically for energy loss caused by heat dissipation within the distribution system. The modeling of the distribution system also must include all vital switches and switching configuration so that a complete network array can be simulated. All power demands (loads) must be modeled, whether the loads are simple power amplifiers or more complex motors, the energy demand of which depends upon torque requirements. The loads should be accompanied by V-I curves and temperature limitations where possible. Finally, when all the data just discussed are obtained individually, the data must be integrated into a package that represents the entire subsystem.

Consumables Prediction

The level of detail or capability to plan an operationally feasible mission is related directly to the level of knowledge about the consumables subsystem. Specifically, the consumables analyst must consider the following factors.

1. Capacity of usable consumables

2. Operational constraints and philosophies

3. Planned operations

4. Performance characteristics

5. Biases, dispersions, and contingencies

Capacity. - The capacity of usable consumables is an elusive quantity to define. It is a function of loading, trapped propellant, gaging inaccuracy, sampling, and operational-usage procedures. Usage procedures require that the consumables for the mission plan be predicted before the usable capacity can be determined. An example of this situation is the RCS, which has a variable mixture ratio for the bipropellant consumables. This ratio varies appreciably from attitude maneuvers that involve the use of short pulses to translation maneuvers at constant thrust. As the mixture ratio varies, so does the amount of remaining oxidizer and fuel. This shift results in an unbalanced ratio at the time of propellant depletion. The amount of unbalanced propellant then must be classified as unusable or outage.

Operational constraints. - Operational constraints define how, when, and in what environment the consumables subsystems can be used. The constraints are defined by the design specifications, system testing, and flight experience. Once defined properly, the constraints help establish mission rules and procedures. However, if operational procedures must change, then the constraints must be reviewed to determine if they are still valid.

Planned operations. - The planned operation of the consumables subsystem must be known in order to evaluate the required consumables. Because of redundancy in system design, some consumables subsystems can be operated in different ways. Therefore, the consumables analyst must know the proposed operational procedure of each system. Once the planned operational use of the system has been determined, it may become necessary to replan the use of the subsystem because of operational constraints or the lack of usable consumables. Second only to data accuracy, operational procedures have the greatest effects on the capability of the consumables analyst to predict preflight budgets. For this reason, it is imperative that a close relationship be maintained with the organization that defines the procedures to be used on a particular flight.

Performance characteristics. - The system-performance characteristics must be known before a consumables budget can be predicted. Usually, performance characteristics used by the system designer are analytical. Only after the system hardware has been built and tested can these analytical analyses be verified. In some cases, the hardware test cannot be made until the system is actually flown. Therefore, the uncertainty in system-performance characteristics is a major contribution to consumables-budget-prediction inaccuracies. The scope of performance data available on a system usually dictates the degree to which a system must be analyzed. The accuracy of the data is a direct function of the accuracy of the prediction capabilities. Unfortunately, performance data usually are obtained as a second-order priority from tests conducted to verify the operational range of the system. In some cases, data that could have benefited the consumables analyst were not even recorded. In other cases, the data were recorded but lacked sufficient information on how the test was conducted. It has been proven that the best data are obtained from evaluation of preflight simulations in which the flight crew performs the planned operational procedures.

Biases, dispersions, and contingencies. - The formulation of a consumables budget presents some interesting factors that are unique in mission planning. Perhaps the category of operational contingencies is the most nebulous. This fact is evident when the budgets for the systems are examined for the dispersion and contingency (biases) allowances. What quantities are biases and what quantities are dispersions sometimes is a matter of definition or philosophy. The service module (SM) RCS budget is an example of budgeting that has been formulated to satisfy two requirements: propellant for the nominal planned usage and propellant for hypothetical situations that may be encountered. Because hypothetical situations (contingencies) are a function of the flight plan, their magnitude changes as various phases of the mission are completed. The consumable analyst finds that large quantities of propellant are available for mission operations after almost all the major events have been completed (such as lunar module (LM) rendezvous and docking). Therefore, large quantities of SM RCS propellant may be returned to earth or they may be planned for use on scientific experiments which would be executed after the command and service module (CSM)/LM rendezvous.

Assumptions are important in the mathematical formulation of the dispersions and contingencies. Usually, dispersions are root sum squared. Contingencies are considered as independent quantities and are subtracted directly from the remaining consumables to define the margins. The most difficult problem in defining dispersions is to determine whether the quantity is an independent variable or if it can be root sum squared with the other contributors. The LM ascent-stage dispersion is a good example for this problem. The uncertainties for fuel loading, oxidizer loading, trapped fuel, trapped oxidizer, specific impulse I_{sp}, thrust and navigation, lift-off weights, and mixture ratio are root sum squared to obtain one value for three sigma (3σ) dispersion. In some areas, the uncertainties just mentioned are themselves considered to be 3σ values.

PREDICTION EXPERIENCE

Some specific prediction experience in the propulsion, the environmental control, and the electrical subsystems are presented in this section. The accuracies of the consumables predictions for the Apollo 7 to 11 missions are summarized in table I.

TABLE I. - ACCURACY OF CONSUMABLES PREDICTIONS

FOR THE APOLLO 7 TO 11 MISSIONS

Item	Deviation,[a] percent				
	Apollo 7	Apollo 8	Apollo 9	Apollo 10	Apollo 11
CSM oxygen (O_2)	-16	-9	-3	--	-2
CSM hydrogen (H_2)	-6	-7	-1.5	6	-2
Command module (CM) RCS	8.7	1.8	2.4	4	NA[b]
SM RCS	6	--	16	-21	--
SPS	4.6	1.2	2.5	--	--
LM descent-stage EPS			-20	1	-5
LM ascent-stage EPS			-17	-3	2
LM descent-stage water (H_2O)			-6	--	--
LM ascent-stage H_2O			-21	--	--
LM descent-stage O_2			-10	--	-16
LM ascent-stage O_2			-5	-19	-20
Descent propulsion system (DPS)			--	--	3
Ascent propulsion system (APS)			--	--	2
LM RCS			-10	-5	10

[a]A negative deviation is indicative that actual usage was less than was budgeted. Where no deviation is indicated, actual usage is within 1 percent of the budget. The deviation percentage was computed by use of the following formula.

$$\frac{\text{actual usage - predicted usage}}{\text{usable consumable}}$$

[b]No data were available on the CM RCS usage during the Apollo 11 entry because the data-storage equipment was off.

Service module. - The SM RCS has an expected loading of 1342 pounds of propellant; however, only 1220 pounds are available for mission planning. This difference represents 9 percent of the total propellant load. As indicated in table II, gaging inaccuracy accounts for 6 percent of the total loaded propellant being unavailable. Gaging is based on a pressure-volume-temperature relationship. The accuracy of the gage on board the spacecraft is ±10 percent, provided the astronaut has a nomograph to use to correct gage-reading temperature effects. Without the nomograph, the maximum onboard propellant-gaging-system error increases to 15 percent at the 0 percent usable-propellant-remaining point.

TABLE II. - PROPELLANT-LOADING DATA FOR THE

SERVICE MODULE REACTION CONTROL SYSTEM

Description	Propellant required, lb	Propellant remaining, lb
Expected loading	--	1342.4
Initial outage caused by loading mixture ratio	15.6	--
Total trapped	26.4	--
Gaging inaccuracy	80.4	--
Deliverable	--	1220.0

Another major contributor of unusable propellant is the mixture-ratio effect. The quantity of propellant outage predicted for loading is shown in table II. Additional outage for mixture-ratio shift is a function of the mission plan. On the Apollo 11 mission, a mixture-ratio outage of approximately 6 percent unusable of total loaded propellant was noted. Advance missions probably will involve larger mixture-ratio outages because of an increased amount of CSM-alone attitude maneuvering that will necessitate the use of minimum impulse.

The ullage-maneuver requirements and the LM-rescue allowances also have appreciable effects on the consumable budgets. The ullage-maneuver requirements are defined by the time required to settle the service propulsion system (SPS) propellant in the sump tanks. The maneuvers are required only after the SPS propellant has been depleted in the storage tanks. For critical situations, the SPS can be started without an ullage maneuver. The LM-rescue allowance is incorporated into the mission redline and is defined as a certain quantity of usable propellant that must be remaining before rendezvous.

Originally, the SM RCS tanks were designed to contain 790 pounds of usable propellant. Budgets for the design reference mission were estimated at approximately 250 pounds, which gives a very good margin for contingency and dispersion allowances. In November 1967, the Apollo Configuration Control Board defined the budget to be 409 pounds for the nominal Apollo 11 lunar mission with a rescue allowance of 520 pounds. These requirements made it necessary to add extra propellant tanks to provide 1220 pounds of usable propellant. However, the predicted budget continued to increase as the mission procedures became better defined. The final budget for the Apollo 11 mission was predicted to be 590 pounds, more than a 100-percent increase over that defined for the design reference mission. The actual usage during the mission was 580 pounds, which is representative of a prediction error of 2 percent when all procedures have been defined.

The SM RCS budgets have continued to increase, and it is expected that these budgets will reach a usage level of 800 pounds for the Apollo 15 mission. The increase is because of the scientific experiments performed on the mission. The SM RCS budget predictions for the Apollo 8 and 11 missions were in agreement with the flight data. The Apollo 7 SM RCS predictions were 6 percent less than the actual requirements. During the braking phase of rendezvous, 35 pounds more propellant was consumed than had been predicted, and approximately 20 pounds of propellant were consumed during the period of the fifth SPS burn (the cause was not determined). The Apollo 9 SM RCS propellant budget prediction was 16 percent less than the actual requirements. Significant deviations occurred in the following phases.

1. Transposition and docking
2. Undocking for rendezvous
3. Rendezvous
4. LM jettison

In contrast, the Apollo 10 SM RCS propellant usage consistently was above the budgeted profile. The predictions were 21 percent more than the actual requirements and can be attributed to the following causes.

1. Improved passive-thermal-control mode
2. Efficient execution of transposition and docking maneuvers
3. Midcourse correction budgeted but not required
4. Efficient execution of translunar navigation sightings
5. Efficient execution of docking and postdocking activities

Lunar module reaction control system. - Fifteen percent of the loaded propellant for the LM RCS is unusable for mission planning: 3 percent is mixture-ratio outage, 6 percent is for gaging, and 6 percent is trapped. Increases in total percentage unusables compared with the 9 percent for the SM RCS result primarily from the propellant trapped in the lines to the thrusters. The CSM has a quad arrangement with tanks for each four sets of thrusters, whereas the LM RCS has a central location for propellant tanks and has long lines to the four sets of thrusters. This loss in LM RCS usable propellant is offset by not having to account for quad imbalance dispersion. The usable propellant is defined in table III. Unlike the SM RCS, the LM system has the capability of using propellant from the APS main propellant tanks. To ensure that the propellants are settled properly in the APS tanks, the RCS must perform an ullage maneuver to prevent helium, which may be trapped below the propellant in the APS tanks, from being ingested through the interconnecting lines to the RCS thrusters.

TABLE III. - USABLE-PROPELLANT DATA FOR THE

LUNAR MODULE REACTION CONTROL SYSTEM

Description	Propellant required, lb (a)	Propellant remaining, lb (a)
Loaded	--	633.0
Trapped	40.6	592.4
Gaging inaccuracy and loading tolerance	39.5	552.9
Mixture-ratio uncertainty	17.0	535.9
Usable	--	535.9

[a]Experience in loading is indicative of an error of less than 1 percent.

No propellant allowances are made for contingencies. However, dispersions associated with man-in-the-loop allowances in the nominal budget offset all considerations for system dispersions. Therefore, dispersions and contingencies are not considered in the overall consumables budget.

Initial estimations of the operational requirements by the systems designer were indicative that the lunar-landing propellant budget was approximately 392 pounds, considerably higher when compared with the 300-pound budget that was planned for the Apollo 12 mission. Major differences in the budget are in the propellant usage estimated initially for attitude control during descent propulsion system burns, landing requirements, and propellant required for the rendezvousing of the ascent stage with the CSM. This trend of requiring less than predicted is different from that experienced for the SM RCS; however, the operational modes of the LM RCS are limited to performing two tasks: landing and rendezvousing with the CSM. Predictions were also improved considerably when the consumables analyst monitored the flight crew during their simulations. By monitoring the flight crew, the consumables analyst was aware of the techniques and procedures which that particular crew may have elected to follow for its mission. In fact, the major contributor to the improvement in propellant predictions have been monitoring flight crews during simulations.

The history of the LM RCS budgets has never been indicative that this system had marginal propellant reserves. Propellant margins always have been approximately 20 percent of the total loaded propellant. This allowance has been considered sufficient to assist in any anomalies, such as landing-site redesignations and RCS cycling during DPS burns. Also, the capability of the system to transfer propellant from the APS main tanks has influenced this conservatism significantly.

The LM RCS propellant budget was conservative by 10 percent for the Apollo 9 mission. For the Apollo 10 mission, the LM RCS usage reflected the control-mode problem that occurred immediately after staging, resulting in excessive consumption at that point. During the remainder of the Apollo 10 rendezvous, the actual propellant consumption was less than was budgeted. The increased hover time caused a 10-percent increase in LM RCS propellant for the Apollo 11 mission.

Command module reaction control system. - Definition of the usable propellant for the CM RCS has not been quite as extensive as for the other reaction control systems. Unusable propellant represents almost 15 percent of the loaded propellant. As in case of the LM RCS, trapped propellant is a major contributor of unusable propellant because the propellant is transferred from the storage tanks by means of long lines to the thrusters. The CM RCS is completely redundant, having two sets of propellant tanks and thrusters.

The propellant required for operational use on lunar missions is only 17 percent of the total loaded propellant, which leaves approximately 68 percent of the propellant loaded as margin. The main reason for this excessive margin is that the system is completely redundant in order to ensure that proper attitudes can be maintained at all times during hyperbolic-entry velocities. Nominal usage has been within 10 percent of usages predicted for the actual flights. However, there is no consideration for offloading propellant from the system. The CM RCS predictions deviated less than 10 percent for the Apollo 7 to 10 missions. Flight data are not available for the Apollo 11 mission.

Main Propulsion

Service propulsion system. - The percentage of unusable consumables for the SPS is 1.5 percent of the total loaded propellant. This percentage is a magnitude of 10 smaller than those discussed previously for the reaction control systems, partly because the system designers must be concerned with the weight penalties imposed by large quantities of unusable propellant. Approximately 1 percent of the unusable propellant is attributed to trapped propellant; the remainder is attributed to outage and unbalance meter use of the propellant utilization (PU) system. Trapped propellant is located in the engine feedline, retention reservoirs, transfer line, and in the form of vapor. Trapped propellant weighs approximately 440 pounds. The amount of unusable propellant caused by outage is fairly small when the fact that the PU system is operating correctly is considered. However, inaccuracies in the gaging system can result in failure to identify when an outage is occurring until after the capability of the system to correct the outage has been exceeded.

Premission SPS propellant predictions were within 5 percent of the actual requirements for the Apollo 7 to 11 missions. In general, the larger deviations were the result of actual burns being longer than were planned premission.

Descent propulsion system. - The DPS unusable consumables comprise approximately 1.2 percent of the total loaded propellant. As in the case of the SPS, the major contributor of unusables is that propellant which is trapped and unavailable. The other contributors are outage and gaging uncertainties. Propellant allotted for contingencies and dispersions also must be considered as unusable for mission-planning purposes. Dispersion allowances represent approximately 2 percent of the total loaded propellant, accounting for I_{sp}, thrust, weight, and mixture-ratio uncertainties. These values are root sum squared to account for the total contribution to the unusables. Other unusables that must be accounted for are those defined as contingencies. Contingency propellant allowances were made for engine valve-pair malfunctions, redesignation of landing site, and low-level sensor uncertainty. Unlike the dispersions, these values were not root sum squared, but were considered as separate occurrences (biases).

There are two major constraints that the consumables analyst must consider in planning DPS burns. First, because the pressurization system involves supercritical helium, a considerable period of time is required after loading to reach the operational pressures. When this system has reached operational pressure, a consumables analyst must concentrate on the duration of the DPS burns so that the integrity of the pressure system will not be violated. Another major consideration is that the variable-thrust DPS is equipped with an ablative nozzle. Burn durations must be monitored to ensure that the nozzle will not be burned through.

The primary purpose of the DPS engine is to perform the descent burn to the lunar surface. However, a contingency situation could require that the DPS make the transearth injection burn. Nominally, the DPS will require a velocity increment ΔV of approximately 6600 fps for LM landing. However, if the astronaut assumes manual control of the spacecraft, performs a site redesignation, or extends the hover time, this ΔV budget would increase; therefore, these items have been included in the nominal budget considerations. In fact, the budget allows for an additional 2 minutes of hover time when the LM has reached an altitude of 500 feet.

The DPS propellant predictions for the Apollo 9 and 10 missions were in agreement with flight data within less than 1 percent. However, during the Apollo 11 mission, excessive propellant usage was directly attributable to the manual maneuvering that was performed in descent-guidance-program 66. This program was entered at approximately 400 feet to avoid a large crater. Until that time, propellant usage was nominal. Allowances for manual hover and site redesignation were in the preflight budget, but were not considered part of nominal usage. The Apollo 11 deviation was only 3 percent.

Ascent propulsion system. - As is the case for the other major propulsion systems, the unusable propellant for the APS consists of trapped and outage propellant. The values represent approximately 1.2 percent of the total loaded propellant (approximately 63 pounds). An additional 1.2 percent is allotted for dispersions, and contingencies comprise almost 2 percent. Contingencies are composed of engine valve-pair malfunction, out-of-plane corrections, and RCS balance couples requirements. Consideration of all the unusables results in an allowance of approximately 4 percent of the total loaded propellant. The APS propellant predictions were within 1 percent of the flight requirements for the Apollo 9 to 11 missions.

Environmental Systems

Command and service module cryogenics. - The CSM ECS and EPS are integrated to use compatible consumables for fuel-cell operation and life support. Cryogenic hydrogen and oxygen are the consumables for the EPS; their unusables are presented in table IV to define the planning allowance. No allowances were required for sampling, loading uncertainties, and system leakage.

TABLE IV. - UNUSABLES DATA FOR THE ELECTRICAL POWER SYSTEM

Description	H_2, lb	O_2, lb
Total loaded	58.60	660.20
Less residual	2.32 (4 percent)	13.00 (2 percent)
Less instrumentation error	1.50 (2.5 percent)	17.50 (2.5 percent)
Available for mission planning	54.78	629.70

For the Apollo 7 mission, the oxygen and hydrogen deviations from the premission predictions can be attributed to the following circumstances.

1. A 30-pound venting allowance was used in preflight for oxygen, but the tank did not vent in flight.

2. The specification ECS oxygen-usage rate of 0.53 lb/hr was used for premission predictions, but the actual usage rate was approximately 0.36 lb/hr.

3. Cyclic components (heaters and so forth) cycled less than was anticipated, causing a decreased oxygen and hydrogen EPS requirement.

For the Apollo 8 mission, the oxygen and hydrogen deviations from the premission predictions can be attributed to the following circumstances.

1. The ECS oxygen-usage rate was less than the specification value.

2. The total fuel-cell current level was 5 to 7 amperes less than the premission predictions, causing the predicted requirements for oxygen and hydrogen to be higher than the actual flight data.

The deviation in fuel-cell current was caused by uncertainty in equipment duty cycles and by the conservative values for equipment power levels given in the Spacecraft Operational Data Book.

The Apollo 9 CSM oxygen and hydrogen requirements were within 3 percent of the predictions, which was considered quite acceptable. The Apollo 10 CSM oxygen predictions were less than 1 percent from the actual nominal requirements. However, approximately 167 hours after lift-off, fuel cell 1, which was malfunctioning, was purged with hydrogen. Difficulty in terminating the hydrogen flow resulted in a 6-percent deviation between actual and premission predicted hydrogen usage. The CSM oxygen and hydrogen requirements for the Apollo 11 mission were both 2 percent less than predicted, probably because of the loss of an oxygen tank heater element plus a probable reduced RCS heater duty cycle.

Lunar module water. - The LM ECS water budget (table V) has 8 percent unusables for the descent stage and 5 percent unusables for the ascent stage. The tank-loading uncertainty is based on telemetry- and gaging-inaccuracy errors because the telemetry-measuring device is the one used when the tank is loaded. Because the water fill source that is used for the ascent and descent stages is the same, no samples were taken from the ascent stage. In the future, sampling quantities may be increased to 15 pounds; to account for this additional requirement, the extra sampling quantity will be loaded.

TABLE V. - LUNAR MODULE ENVIRONMENTAL CONTROL SYSTEM

WATER BUDGET

Description	Descent-stage H_2O, lb	Ascent-stage H_2O, lb
Loaded	252.0	85.0
Sampling	12.0 ([a]3.6 percent)	--
Residual	5.2 ([a]1.5 percent)	1.6 (1.9 percent)
Loading uncertainty	9.7 ([a]2.9 percent)	2.6 (3.1 percent)

[a]Based on a maximum tank loading of 333 pounds.

The LM ascent- and descent-stage water predictions for the Apollo 9 mission deviated significantly from the actual flight data, primarily because of real-time flight-plan changes, causing a decrease in actual usage. The Apollo 10 and 11 water predictions were in agreement with the flight data.

Lunar module oxygen. - The LM ECS oxygen budget is the one exception to the unusable range of 5 to 8 percent. With its redundancy and small size, the ascent oxygen system presents an unusable allowance of 17 percent. Close examination of the data in table VI is indicative that rounding off these small quantities has introduced excessive percentage errors. The accuracy in the calculation or measurement of these small quantities is another factor that increases the magnitude of error.

TABLE VI. - LUNAR MODULE ENVIRONMENTAL CONTROL SYSTEM OXYGEN DATA

Description	Descent O_2, lb	Ascent 1 O_2, lb	Ascent 2 O_2, lb
Loaded	48.0	2.4	2.4
Residual	0.8 (1.6 percent)	0.1 (4.2 percent)	0.1 (4.2 percent)
Loading uncertainty	1.5 (3.1 percent)	0.1 (4.2 percent)	0.1 (4.2 percent)
System leakage	1.3 (2.7 percent)	0.2 (8.4 percent)	0.2 (8.4 percent)
Available for mission	44.4	2.0	2.0

The Apollo 9 to 11 LM oxygen-usage predictions were higher than were the actual requirements because the LM cabin-oxygen leak rate was much less than the specification value. The actual leak rate was approximately 0.05 lb/hr compared with the specification rate of 0.2 lb/hr.

Electrical Subsystems

Lunar module electrical power subsystem. - The EPS provides all the power that is necessary for the LM to complete a mission. Basically, the EPS consists of four descent batteries (batteries 1 to 4), two ascent batteries (batteries 5 and 6), a deadface relay box, two inverters, two alternating-current buses, and two main direct-current buses.

Electrical power system trapped unusables for the Apollo spacecraft batteries are generally undefined. The batteries are given an initial rating or capacity, which is actually a performance capability guaranteed by the battery manufacturer. Other unusables that are accounted for are based on a lack of Manned Space Flight Network (MSFN) coverage. This allowance covers those periods (usually on the back side of the moon) in which the usage rate is unknown. Also, an allowance is made for the uncertainty in the amount of power the equipment draws, which is usually approximately 2 percent of the total energy used. The unusables considered for a typical lunar mission are given in tables VII and VIII. The LM EPS usage planned for a typical lunar mission is shown in tables IX and X.

TABLE VII. - LUNAR MODULE DESCENT-STAGE UNUSABLES DATA

FOR A TYPICAL LUNAR MISSION

Description	Required power, A-hr	Remaining power, A-hr
Initial capacity	--	1600
Unusable based on lack of MSFN coverage	5	1595
Telemetry unusable	74	1521
Dispersion unusable	23	1498

TABLE VIII. - LUNAR MODULE ASCENT STAGE UNUSABLES DATA

FOR A TYPICAL LUNAR MISSION

Description	Required power, A-hr	Remaining power, A-hr
Initial capacity	--	592
Unusables based on lack of MSFN coverage	3	589
TM unusables	13	576
Dispersion	5	571

TABLE IX. - LUNAR MODULE DESCENT STAGE ELECTRICAL POWER SYSTEM USAGE DATA

Description	Required power, A-hr	Remaining power, A-hr
Required through landing	311	1187
Required for surface time	794	393
Total mission requirement	1105	--
Total usable margin	--	393

TABLE X. - LUNAR MODULE ASCENT STAGE ELECTRICAL POWER SYSTEM USAGE DATA

Description	Required power, A-hr	Remaining power, A-hr
Required through docking	246	325
Required through impact	175	150
Total mission requirement	421	--
Total usable margin	--	150

The Apollo 9 LM EPS descent- and ascent-stage consumables predictions were approximately 20 percent higher than the actual requirements. The following factors were causes of the deviations.

1. The actual RCS heater duty cycle was less than that used for premission computations.

2. The forward-window heaters were turned off during extravehicular activity and rendezvous for the actual mission but were left on in the premission calculations.

3. Other heater duty cycles, such as abort sensor assembly heaters, inertial measurement unit heater, landing-radar heater, and rendezvous-radar heater, averaged less than 2 amperes during the actual mission compared with 4.5 amperes for the premission predictions.

4. The total time during which the LM descent stage was active was reduced by 1.5 hours during the flight.

The Apollo 10 descent and ascent premission EPS predictions deviated 3 percent or less from the flight data. Primarily, the real-time departures from the premission flight plan with respect to the duration of the LM housekeeping day, load sharing between the ascent and descent batteries, and a delay in the parallelling procedures were responsible for the deviations. The Apollo 11 LM EPS premission consumables predictions were within 5 percent of the flight requirements. The deviations appeared to be the result of using a slightly high RCS heater duty cycle for the premission predictions.

Command and service module electrical subsystem. - The CSM EPS is comprised of cryogenic fuel cells, entry and postlanding batteries, and pyrotechnic batteries. Two pyrotechnic batteries are used to fire ordnance devices. These batteries are isolated from the rest of the EPS; however, any of the three entry and postlanding batteries can be used to initiate pyrotechnic circuits. No consumables budgets were required for the pyrotechnic batteries.

In budgeting for the cryogenics consumables requirements, the consumables analyst must first define the quantity in the tank at lift-off. After the fuel cells are pressurized, cryogenics use must be started or an overpressure condition will occur. To prevent overpressure, the tanks must be vented or the cell purged for impurity buildup. Additional cryogenics are required for prelaunch electrical-power checkout. Flight cryogenics requirements are based on the spacecraft electrical loads. Electrical loads are defined in a manner similar to the LM/EPS analysis previously defined.

In predicting the cryogenics usage, the consumables analyst also must consider the mission redline. Generally, redlines have been defined as the minimum quantity of cryogenics necessary to complete an electrical powered-down return to the primary landing area on a single tank from the most critical point in the mission. Budgeting experience was reported in the environmental section.

RECOMMENDATIONS FOR ADVANCED SYSTEMS

Gaging

An examination of table XI indicates that one area in definite need of improvement is the consumables allotment for unusables. The allotment ranges from 1 percent to 15 percent. The low of 1 percent is misleading because this represents a DPS unusable

TABLE XI. - APOLLO CONSUMABLES REQUIREMENTS

System	Unusable consumable, percent	Quantity required for nominal lunar mission, percent	Nominal remaining, percent	Biases and dispersions, percent (a)	Margin, percent
LM RCS	15	65	20	NA	20
SM RCS	9	68	23	NA	23
CM RCS	15	17	68	NA	68
CSM SPS	1.5	90	7.5	4.2	3.3
LM APS	1.2	93	5.8	2.8	3.0
LM DPS	1.1	93	5.9	4.0	1.9
LM descent-stage O_2	7.5	65	27.5	3.0	24.5
LM ascent-stage O_2	17	23	60	2.0	57
LM descent-stage H_2O	8	50	42	11	31
LM ascent-stage H_2O	5	49	46	7	39
CSM O_2	5	75	20	4	16
CSM H_2	6.5	80	13.5	1.9	11.6
LM descent-stage batteries	.0	69	31	6.4	24.6
LM ascent-stage batteries	.0	42	58	3.0	55.0
CSM batteries	.0	86	14	4	10

[a]NA = not applicable.

of approximately 170 pounds, a considerable mass to be carried to the moon and not used. The errors that are associated with gaging are the primary area for improvement in the unusables for all consumables systems. If the gaging errors can be improved, a major step will have been achieved. Gaging errors were recognized in the early design of Apollo systems. A nuclear system was planned that would improve the gaging prediction for the reaction control systems. However, this design was unfeasible, and the old pressure-volume-temperature gaging method was adapted. Gaging error exists not only for the ground-based calculation, but also is found in onboard crew read-outs. Some onboard errors are so large that crew charts must be prepared to correct them to a 10-percent accuracy. Better gaging for propulsion systems would eliminate other types of unusables, such as mixture-ratio shifts. Gaging inaccuracy problems are not limited to the propulsion system but occur in the operation of all of the consumables system.

Redundant Operation Modes

In the interest of safety, the Apollo spacecraft was designed to include redundant systems. Initially, the systems were referred to as primary and secondary systems. After these systems were developed, it was discovered that the secondary systems had primary functions. As a result, the flight crew was given a choice as to which system they preferred, a choice that sometimes was made after the flight had begun. The major objection to this operation is that, generally, the consumables rates are different between the primary and secondary systems, which makes it very difficult to predict consumables budgets. For example, there are more than 20 ways to translate the CSM, and each procedure results in a different rate of consumables expenditure.

Consumables Transfer

The transfer of consumables from one system to another has been proven beneficial for the LM propulsion systems. The crossfeed and interconnect have eliminated or minimized problems of propellant management. This solution could have applications for advanced systems that use the same consumable (fuel cells and oxygen-hydrogen propulsion).

To transfer consumables from different space vehicles presents a compatibility problem. This problem was experienced on the Apollo 13 mission with the lithium hydroxide canisters. Commonality should be considered a goal for all spacecraft operating together. Sizes of hoses, electrical loads, materials, and many other facts should be considered for possible exchanges in an emergency. Battery chargers and inverters should be a first-priority compatibility problem.

System Performance

The actual performance that a system achieves in flight is rarely known. Telemetry data have been very good; however, the system engineer or consumables analyst still does not know what the exact performance of his system will be, especially in the case of the main propulsion systems. Generally, it can be determined whether the system performed within its specification limits, but actual performance of the system usually remains a mystery within the accuracy limits of the telemetry for expendable systems.

Usually, system performance is sized for a specific mission. This method of sizing is required in order to give all the system designers the same design goal. However, it is recommended strongly that, at some phase in the system design, proposed alternate missions be investigated. In case a particular alternate mission or a mission required for systems checkout has a questionable consumables margin, possible changes could be made before the system is fabricated.

CONCLUSIONS

From the consumables-analysis experience gained in the Apollo development and early lunar-landing missions, the following conclusions are stated.

1. The consumables analyst must define the consumable available for usage and must know when the system is to be used, in what mode of operation it will be used, and what constraints must be observed.

2. The development of simplified computer models that simulate the consumables systems has proven to be an invaluable tool for use by the system engineer in the evaluation of the consumables budgets. Also, these models have been extremely useful for conducting analyses for management-proposed system redesign. Proper evaluation of the consumables subsystem schematic usually resulted in methods for further reducing the modeling requirements and computation time.

3. Usually, performance data on the system were obtained as a second-order priority in verifying the operational capability of the system.

4. System procedures and the environment in which the subsystems will operate have to be established and identified.

5. All the system requirements, constraints, and assumptions affecting the consumable predictions need to be identified.

6. Monitoring flight-crew techniques during simulations resulted in major improvements in propellant-usage predictions.

7. For some consumables, a system-prediction accuracy of 10 percent is acceptable. Other systems, such as main propulsion systems, necessitate a prediction accuracy of 1 percent to prevent excessive weight problems.

8. Design considerations to be made for advance systems are better systems-quantity gaging, redundant system-performance modes similar to the primary mode, the capability to transfer consumables that are mutually similar to different systems, and a more conscientious documentation of performance data during system tests.

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