Control of Space Shuttle Maintenance Cost by the Application of Airline Methods

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ABSTRACT

This paper attempts to relate certain areas of similarity between Space Shuttle operation and Airline operation. The design controlled factors affecting airline maintenance cost are discussed. The thesis is that the Space Shuttle designer should consider airline experience in areas affecting maintenance cost in order to design the most cost effective Space Shuttle System.

INTRODUCTION

The primary goal of the Space Shuttle is the ability to put men and material into an earth orbit and return them to earth with safety, schedule reliability and at low cost. There is no doubt that NASA working with the aerospace industry can accomplish the first two, that is to operate with safety and schedule reliability. It is the third to operate "At Low Cost" which will present the greatest challenge.

There are many similarities between Space Shuttle and Airline Operation. For that reason, a look at the airline approach to control of recurring costs should be of value to the Space Shuttle designer. Maintenance cost for Pan Am for various aircraft varies between 21% and 33% of overall operating cost and it is not unreasonable to assume that this percentage will be higher on the Space Shuttle because it is the first reuseable space system to be built. Control of Maintenance cost, therefore, can have considerable impact on Space Shuttle recurring costs.

Airline experience indicates four major areas which must be considered during preliminary design if maintenance cost is to be controlled. They are:

1. Fault detection and isolation
2. Redundancy
3. Maintainability
4. A comprehensive maintenance program

Fault Detection and Isolation

The Space Shuttle will be far too complex to be designed for zero failure. Once we accept this we then must design to allow for mechanical failures and system deterioration. Systems must be designed so that failures can be detected and isolated in a minimum of time. In fact we must go further than just the detection of failures. We must be able to detect deterioration and predict failures. This will allow insipient problems to be corrected by preventive maintenance before an actual failure occurs.

The airlines have concentrated on self-contained fault isolation equipment. The basic specification on the B747 was written to include onboard fault isolation in all flight critical systems. This is particularly adaptable to electronic systems and most LRU's include fault indicator lights and fault isolation logic built directly into the component. Where there are several closely interrelated components in a system which makes fault isolation difficult, the approach is to check complete system operation with on-board check-out equipment. An example is the aircraft system for determining gross weight and center of gravity location. On command the computer in this system injects a signal which checks all of the components, wiring and connectors and isolates the fault to zones allowing quick component change to correct the problem. The pay off has been in fewer unconfirmed removals and shorter maintenance down time.

Based on airline experience, when self-contained fault isolation is not installed:

1. More complex G.S.E. and software are required for fault isolation.
2. Troubleshooting time is extended with resultant delays in vehicle release from maintenance.
3. Fault isolation is less accurate where intermittent faults are involved.

All of these increase maintenance cost without a corresponding increase in reliability.

The Space Shuttle must have as a design goal inclusion of on-board self-test equipment in all systems and components if maintenance cost and down time are to be minimized.

Redundancy

With today's "state of the art" it is not possible to detect and correct each incident of deterioration before a system or component failure results. Therefore, in order to insure mission reliability, redundancy as well as reliability must be designed into the system. The depth and type of redundancy required depends on system criticality. But in all cases redundancy must be carefully weighed against increased reliability requirements because maintenance costs rise sharply as reliability requirements increase. This is brought about by:

1. More rigid control of shop limits
2. More exhaustive testing requirements
3. Higher level of technician capability and training
4. More sophisticated shop equipment and cleanliness

System reliability through redundancy with a lower order of reliability can result in a lower acquisition and maintenance cost.

"Designed-In" redundancy allows airlines to dispatch aircraft with systems or portions of systems inoperative. This increases schedule reliability and reduces maintenance cost by allowing repairs to be delayed until a time when parts and man power are available. It is doubtful that this procedure will be applicable to the Space Shuttle during the early stages of operation. As operating experience and confidence increase, it may well be the most cost effective approach.

In airline parlance, redundancy does not necessarily mean that two, three or four identical systems are installed with all except one on standby ready to take over if a failure should occur. This type of redundancy is used in flight critical systems such as the autopilot, autoland and inertial navigation systems but for less critical system redundancy may take one of several forms:

1. In modern aircraft structure due to multiple load paths there is no single point failure which will be catastrophic. For example, if the lower cord of a wing spar fails flight loads will be carried by stringers and wing skin. This reduces the margin of safety but still allows safe flight.

2. In instrumentation pressure indicators are backed up with pressure warning lights so that if either is inoperative mission reliability is not effected.

3. In engine instrumentation several parameters are monitored, due to the interrelation of these parameters, one or more may be inoperative without jeopardizing engine operation.

Maintainability

Maintainability in most cases is the judicious application of engineering know how, experience and common sense. Basically this means to design for simplicity, accessibility, quick replacement and rapid system revalidation after a fault has been corrected. If maintainability is not considered in preliminary design, an aircraft or the Space Shuttle, for that matter, cannot be maintained at low cost. Retrofit to obtain maintainability is extremely costly. In all aircraft acquisitions, and this includes the Shuttle vehicles, the customer must be deeply involved in the preliminary design process to determine that maintainability is not lost in the trade off's with weight, cost and production convenience. Because it is the customer who must pay for maintenance.

A look at the procurement of the B747 from Boeing will illustrate how an airline injects its requirements into the design to obtain maintainability. After a feasibility study and high level agreement that Pan Am was interested in such an aircraft, Boeing submitted the B747 Basic Specification for review. It was at this point that Engineering and Maintenance made a concentrated input to insure maintainability. The changes to the Basic Specification requested by Pan Am read like a textbook in maintainability. These changes were based on Engineering analysis and application of experience with earlier aircraft. A review of that document would be of interest to all who are involved in the Space Shuttle procurement process.

After contract signing the "Detail Specification" became the controlling document for the aircraft. This specification is still maintained although it has been revised 32 times since the original issue. It now reflects our requirements for a second group of B747's which are being delivered later this year. The Basic Specification never remains firm for long. It is continually in a state of change. These changes fall into two categories:

1. Those changes initiated by the manufacturer as a product improvement. Some of these are incorporated at no cost to the customer but others may involve increased cost or penalties in performance or weight.

2. Those changes requested by the customer. They usually reflect service experience on the aircraft in operation or are the result of research and development by the airline or component manufacturers.

In all changes, maintainability is given consideration.

Pan Am invested over 100 Engineering and Maintenance man years during the four year development and procurement process of the B747 but still there were many details which escaped maintainability scrutiny. Some examples will help to clarify this point:

1. When the JT9D engine was designed for the B747, 21 boroscope holes were installed. These holes allow inspection of the suspected trouble areas inside the engine. When Boeing installed the auxiliary equipment on the engine such as plumbing, ducts, pumps, etc., 14 of the 21 holes were obstructed. We now must remove equipment to gain access to these 14 inspection holes. If maintainability had been given proper consideration this would not have occurred.

2. The B747 is equipped with upper and lower rudders for redundancy. At higher speeds less rudder travel is required. To accomplish this a Rudder Ratio Changer has been installed to vary the amount of rudder deflection as an inverse function of airspeed. This system contains two control units, two actuators and one comparator. The actuator motor is designed to operate from the fully extended position of 141 knots to the fully retracted position at 359 knots and the motor is stalled, at the end of actuator travel, at all other times. On the ground, with inadequate cooling, heat build up from the stalled motor overheats the lubricant in the motor bearings and the motor fails. Add to this the requirement for a 40 foot work stand to change the actuator and you have a perfect example of maintainability not being considered in design.

Maintenance Program

The last design consideration and for sure the most misunderstood is the maintenance program. Airlines have experienced a major evolution in maintenance philosophy during the past decade. One of the most important facets has been the change from a fixed time between overhauls to "on-condition" maintenance. "On-condition" means that the inspection, check and replacement of a component or system and the extent of refurbishment and testing required is best determined by the condition of that component or system. System condition is determined by one or more of the following:

1. Flight Crew Observations
2. On-Board Monitoring
3. Visual Checks
4. Ground Checks using Aircraft Instruments
5. Ground Checks using Ground Test Equipment
6. Non-Destructive Testing
7. Monitoring and Analysis of Performance Data

In the development of a maintenance program there are certain concepts which should be understood.

1. Safety is not a negotiable item. There are minimum safety standards established by the airline and by federal regulations which must be complied with. Safety is of prime importance in any acceptable maintenance program.

2. Maintenance which is not required not only imposes an economic penalty but degrades reliability. A few years ago when major overhauls were accomplished on aircraft, the trouble rate was invariably highest during the first 200 to 300 flight hours after release from overhaul. This resulted from infant mortality of overhauled units installed as well as from problems introduced by inattention to details or slips in quality control.

3. The maintenance program and the compatibility of the aircraft to that program must be developed and confirmed before the aircraft reaches the operational stage.

A look at the B747 Maintenance Program and its development should be of value during the procurement phase of the Space Shuttle. Working with other airlines and with the FAA, a preliminary maintenance plan for the B747 has been established. Structural inspection items are all on a sampling basis. Feedback from inspection findings to the system establishes the frequency and number of future inspections. Component removals are not specified by fixed time between overhaul but rather a procedure has been established where system and components will be monitored for condition and the feedback will determine if a fixed time between removal is required.

The removal of a component from the aircraft is scheduled when deterioration occurs as evidenced by monitoring or when a malfunction renders the unit partially or totally inoperative. Once the component is removed, the shop processing is of importance to reliability as well as cost. With rare exception, we no longer overhaul components. By overhaul we mean to return the component to original manufacturers specifications in all areas. Rather than overhaul, we repair the trouble reported and refurbish those areas which are known to be subject to wear or deterioration.

The work required on a component when it reaches the shop is determined by the information obtained from monitoring, from flight crew reports, from the mechanic removing the component and by a preservice test of the component. The pre-service test is made primarily to determine if the unit has actually failed and if so, to define what is required to restore the unit to an airworthy condition. The component is then repaired to the extent necessary to correct the problem found, tested, and put in stock for reinstallation. During shop repair, service limits are used and components are not normally returned to original design specifications. The component is tested only to the extent necessary to check the work that was done and the affect that work would have on the rest of the component. The rationale behind this is as follows: Consider a complex component with many parts - when a single part fails, the component malfunctions. If the part had not failed, the component would have continued to function normally. Therefore, replacement of the failed part and testing component operation is all that is necessary to restore this complete component to an airworthy condition.

Since the change from a "Fixed Time" to an "on-condition" Maintenance Program on the 707 and 727 aircraft, Pan Am has experienced no increase in flight crew reported items, there has been no increase in the delay rate, and overall component unscheduled removal rate has been reduced. In addition to the reduction of the unscheduled component removals, all scheduled removals for components which are "on-condition" have been eliminated. This has reduced maintenance cost significantly. In 1969 approximately 18,000 component time limit removals were eliminated. The reduced shop workload amounted to an estimated $2,200,000 for material and $3,800,000 for labor. The reduced aircraft workload for removal and installation of the components is estimated at $575,000 for a total 1969 savings of over $6,500,000. Although no dollar figure has been assigned, it also resulted in reduced aircraft down time.

The maintenance plan contains servicing items such as lubrication, area inspection, fluid quantity checks, tire pressure checks and so forth which are specified at fixed times. But even these times are negotiable and during the first year of operation we have extended and reduced many of these service periods to fit the needs of the system.

We maintain aircraft by monitoring operation, inspecting the airframe, engines and systems, and by giving them all a good "letting alone". In one sentence, that outlines the Modern Airline Maintenance Philosophy and we predict that it will some day be the basic maintenance plan of a "Low Maintenance Cost" Space Shuttle.