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AIAA SPACE FLIGHT TESTING CONFERENCE
COCOA BEACH, FLORIDA MARCH 18-20, 1963

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To be Given by F. J. Bailey, Jr.
at the AIAA Space Flight Testing
Conference, Cocoa Beach, Florida
March 18, 1963

REVIEW OF LESSONS LEARNED IN THE MERCURY PROGRAM RELATIVE TO SPACECRAFT DESIGN AND OPERATIONS

Introduction

The papers presented so far in this session have described specific measures taken in preparing the launch vehicle and spacecraft for Mercury missions. The purpose of the present paper is to review, in somewhat more general terms, some of the more significant lessons learned in the Mercury program, to see where changes or additional measures may be desirable in future programs. (Slide #1)

The lessons that have been learned fall broadly into two main areas, the first applying to program planning, the second to detailed design.

Lessons with significant implications as to program planning are indicated in this slide.

Flexibility to Absorb Change

In this area, perhaps the most important lesson learned is that designs, procedures, and schedules must have the flexibility to absorb the steady stream of changes that will be generated by a continually increasing understanding of space problems, and by equipment malfunctions that will occur during system development testing. Reliability, quality control, manufacturing, and procurement plans must all be set up with full recognition of this requirement for continual hardware change.

This requirement is a consequence of the rapid advance of our space flight capability. We must undertake detailed design of spacecraft for the next program long before flight experience from the preceeding program has been digested and disseminated. Under these conditions, we are sure to make incorrect design decisions that will have to be corrected before flight.

Equipment malfunctions will also occur, particularly during subsystem development testing. In manned flight we must regard every malfunction, and, in fact, every observed peculiarity in the behavior of a system as an important warning of potential disaster. Only when the cause is understood and a change to eliminate it has been made and verified, can we proceed with the flight program.

The problem here is one of shortening the failure analysis - corrective action cycle. The conventional procedure of sending the failed part back through the contractor and sub-contractor to the parts vendor for failure analysis has proven to be completely unsatisfactory for our programs. To the maximum extent possible, failure analysis and decisions as to corrective action should take place immediately at the scene of the failure, where there is the best opportunity for accurate determination of the pertinent facts. Contracts and purchase agreements with component and parts suppliers should provide that the services of their engineering staffs will be available on call whenever required for this purpose.

Subsystem Segregation

One way of increasing the flexibility to absorb change is by subsystem segregation; that is, by designing from the start to minimize the interactions between subsystems. In accelerated programs such as Mercury, it is absolutely necessary that the various subsystems be developed concurrently by widely separated groups of specialists. If the subsystems can be designed to be completely independent of one another, their development testing, and any redesign resulting from it, can be completed before assembly of all the subsystems into the spacecraft for integrated system tests.

If the subsystems are designed to be highly interdependent, no matter how carefully the activities of subcontractors are coordinated, it is almost a certainty that difficulties requiring substantial redesign will be encountered during the integrated system tests. At this late stage in the program, design changes have much more serious effects on cost and schedule than would similar changes at an earlier stage.

The most likely area for trouble of this sort is in electrical systems where, for example, time delay devices and programmers have been very seriously affected by the electrical transients which result from actuation of pyrotechnic devices. Another major trouble area of this same type has been the adverse effects on equipment of heat generated in adjacent equipment that was designed without adequate attention to safe disposal of this heat.

Quality Control

The quality control problem involved in the production of our early spacecraft is quite different from that encountered in the past with aircraft or missiles. The differences arise from the high overall cost of each space mission, the small number of spacecraft to be produced, and the constraints against testing the flight articles.

The problem is to produce, as quickly as possible, five or ten articles that will operate perfectly the first and only time they are used, rather than to produce, as cheaply as possible, thousands of articles that will operate with an economically tolerable incidence of failure.

In many quality control areas this difference in the nature of the problem must be reflected in a marked difference in procedures and attitude. For example, inspection procedures must be designed to locate and reject every defective or marginal part without regard for how many good parts are unnecessarily rejected in the process.

The amount of proof-testing that can be performed on the actual flight articles is limited by the large numbers of one-shot and limited-life items in the various subsystems and components. In the case of items such as the heat shield, escape rockets, explosive separation devices, explosive disconnects, igniters, etc., the actual specimen to be flown cannot be tested at all. Items such as fuel cells, ablative nozzles, parachutes, and launch vehicle engines can be given only limited tests, under conditions that are not truly representative, and then only at considerable risk that the tests and their aftermath may introduce more flight failures than they prevent.

The operating philosophy that has evolved to meet this situation is based on the idea that randomly selected samples of components can be subjected, in a so-called qualification test program, to appropriate environmental, reliability, and overstress tests with complete confidence that the results of these tests will apply to the remaining articles installed in the flight vehicles. This confidence is justified only if all supposedly identical parts from which the components are assembled are truly identical. Identity in the sense required by this philosophy cannot be fully established by inspection and measurement alone. Features that eventually turn out to be important in governing susceptibility to failure often are unrecognized or inadequately defined by inspection or measurement at the time of manufacture.

To achieve a degree of control over whatever unknown or indeterminate influences may exist, all components requiring certification through a qualification test program should be made up from sets of parts whose members have been produced consecutively on the same assembly line without an intervening change in design, process, or materials.

It is also necessary that the parts be identified as members of the set and that records show the location of all parts in a set. Whenever failure of a component under test reveals a defect in a part it is essential to locate and remove immediately all similar parts from all flight articles. Very strict control over parts identification and use is necessary to insure that all suspected parts, wherever used, can be readily located for removal and replacement.

Configuration Control

Closely related to the problem of quality control is the problem of configuration control, that is being certain that the space vehicle at the time of launch contains only fully qualified items. The large number of widely separated and more or less independent groups responsible for the various stages, systems, subsystems, and components of our space vehicles makes it an extremely difficult task to prevent the introduction of supposedly unimportant design changes that all too often turn out to have an adverse effect on the safety or success of the mission. The difficulty arises most often at the component or parts supplier level, where the spacecraft components are only a small part of the supplier's output and he has no close association with their ultimate use. There is a definite need for improved procedures to guard against these "sneak" changes.

There is also a need for very special procedures to prevent inadvertent re-use of parts that have at one time or another shown symptoms of trouble, but cannot be made to repeat the symptoms. Unless conclusive evidence can be developed proving that the test setup was at fault these parts cannot be accepted for re-use until they have been completely rebuilt in such a way as to positively eliminate all possibility of repetition.

Quantitative Reliability Assessment

In the course of the Mercury program a substantial effort was made to determine the usefulness of conventional techniques of quantitative reliability assessment in manned space flight programs. An attempt was made to get an overall estimate of the reliability of the Mercury spacecraft by using mathematical models of the subsystems together with failure rate data derived from our own actual test experience on the system parts and components.

In general, the results were not satisfactory because the applicability of the failure rate data was always highly debatable. It is a basic ground rule of our approach to manned space flight that a failure during development and preflight tests must always result in a corrective action designed to eliminate all possibility of repetition of that particular type of failure. Hence, past failure data never applies directly to current articles.

In Mercury, the random or statistical type of failure that predominates in fully developed parts has been much less of a problem than has "built-in" or "early development" type of failure that arises from design errors, interaction effects between parts and components, unanticipated environmental effects, or errors in estimating environments.

Virtually all our flight difficulties to date have been in this early development category. Most would have been detected and eliminated before flight if the ground test techniques and programs that were ultimately devised had been available earlier.

As a result of this experience, our feeling as to the role of numerical reliability assessment in manned space programs may be summarized as follows:

> To insure that adequate attention is directed to reliability in the design stage it is desirable to specify an overall numerical reliability goal. This goal should be apportioned or budgeted through a mathematical model down to the various subsystems and their components. The subsystem designer should be required to show that his subsystem is capable of absorbing the expected number of random or statistical type failures of parts without serious consequences or without exceeding his reliability budget.

Beyond this point the usefulness of formal quantitative reliability assessment procedures is debatable. On the basis of our experience the most effective approach from here on is to concentrate on establishing a testing program that will assure detection and correction of all the "built-in" sources of system failure before flight.

Detailed Design

On the next slide (Slide #2) I have listed some of the major things that Mercury has taught us relative to the technical problems of spacecraft design and operation.

Pilot Performance

The most significant finding in the Mercury program to date has been the convincing evidence that the pilot can function effectively in the space environment, and that ground training devices and simulators can provide a realistic evaluation of the effectiveness with which he will be able to perform various tasks in flight.

This demonstration that the space environment does not degrade pilot proficiency is extremely important to reliability. It opens up the space flight field to the tried and proven airplane approach of heavy reliance on the pilot for detection of malfunctions, and for shutdown and switchover to back-up systems or alternate modes of operation.

The pilot's next most important function in space flight will be in establishing and maintaining the attitude of the spacecraft, particularly during the critical periods when its velocity is being changed by application of thrust. Mercury flights have demonstrated that the pilot can successfully determine spacecraft attitude by visual means on both the light and dark sides of the earth and that the angular velocities developed in prolonged drifting flight are neither of appreciable magnitude nor disturbing to him.

The ability of the pilot to tolerate long periods of drifting flight is particularly significant because of the critical importance of minimizing the use of reaction control fuel. Optimum management of reaction control fuel is emerging as one of the most important requirements for successful space flight. The Mercury experience to date has indicated that direct manual control over the reaction control thrust nozzles is apt to be quite wasteful of fuel. Indications are that the ultimate system for spacecraft may be a command type control system where some form of autopilot fires precisely measured and timed pulses to produce commanded rate or attitude changes.

There is an obvious need for research on both the control power and response required in spacecraft and on the mechanization of control systems to meet these control requirements with minimum fuel use.

An associated urgent requirement for future spacecraft that has been brought out in Mercury experience is provision of more accurate and reliable indications to the pilot of fuel usage, both rate of use and quantity remaining.

Although experience in Mercury has been limited to management of attitude control fuel, similar considerations can be expected to apply to management of velocity-changing fuel in rendezvous, orbit correction, and lunar landing maneuvers.

Zero g Environment

Probably the most insidious hazard to reliability associated with the space environment is the possible effect of zero g on spacecraft equipment that is not completely free of debris. In orbit, every void in the spacecraft from the pressurized cabin itself down to the interior of a transistor or relay, including all gas and liquid tanks and lines, becomes a region where debris that would normally be held fairly securely in place by the earth's gravitational field now floats freely about under the influence of magnetic or electrostatic fields, fluid currents, or surface tension forces.

Under these conditions filters and screens become imperative in all liquid and gas systems to protect close tolerance valves, orifices, or impellers. Indeed the most obvious manifestation of the phenomenon in Mercury was the stoppage of the unscreened cabin ventilating fan by debris in two of the early unmanned flights. This debris was present despite clean-room fabrication of the spacecraft, plus a very intensive effort to clear it of debris by repeatedly inverting and tumbling it.

Obvious protective measures also require complete elimination of exposed electrical contacts anywhere that sufficient debris could exist to short them. There may conceivably be still more subtle effects, however, where interactions between electrostatic and magnetic fields and accumulations of floating particles may have significant effects on equipment operation. Since these phenomena, if they exist, cannot be reproduced on earth, a great deal of imagination may be needed to visualize the nature of such problems and to determine the protective measure required. The brute-force solution of perfect cleanliness seems, from past experience, to be unattainable. In any event, it will become more difficult as we move toward micro-miniaturization where smaller and smaller particles of debris become capable of shorting out the more closely spaced electrical paths.

Heat Balance

The problem of removing heat from equipment in spacecraft has given a great deal of trouble. Internal heat generating equipment such as inverters requires special attention because the reduced density of the cabin oxygen atmosphere and the lack of natural convection under zero g conditions inhibits convective heat transfer. Careful design is required to provide adequate forced convection or conductive heat paths to transfer the heat to points where it can be rejected to space by radiators or evaporative coolers. External equipment, notably the nozzles of the reaction control system, has given trouble for the same reason. The vacuum environment eliminates all convective cooling of the nozzles. Special attention is required to prevent heat left in the nozzle walls after each pulse from leaking back by conduction up the propellant feed lines, with adverse effects on the propellant or the solenoid valves that control its flow. A very thorough and careful analysis of the heat flow and temperature conditions in all equipment is an important design requirement for future spacecraft.

Structural Deformations

Because of the requirement for lightness launch vehicle tanks, adapters, and the spacecraft itself are all susceptible to rather large distortions under load. During the atmospheric phase of flight, dynamic pressures approach 1,000 pounds per square foot at Mach numbers in the transonic speed range. Under these conditions fluctuating pressure distributions may produce rather severe buffeting loads and fluctuating wakes. Early in Mercury development flights we ran into several cases where structural reinforcement or redesign was required to prevent failure, or where increased clearances had to be provided to reduce the risk of interference or damage under load.

It is not feasible to duplicate the flight conditions at full scale with ground equipment, nor is it feasible to build up gradually to these flight conditions in a series of manned flights. Hence, each new space vehicle configuration will require at least one unmanned flight to provide verification of structural integrity under the conditions encountered in the atmospheric phase of flight.

Distortion and vibration that might not otherwise be harmful can be disastrous if they trigger limit-switches that are used to sense separation and initiate automatically subsequent steps in the flight sequence. The best protection from trouble of this sort is obtained by designing separation sensors to require travel beyond any possible structural deformation before actuation, and by requiring confirmation of separation by two sensors before activation of succeeding steps.

Experience shows that space vehicles, as they reach the launch pad, do not always agree exactly with the original design. Adequate inspection procedures must be developed and the necessary inspection ports must be provided to insure that the design clearances actually exist in the vehicle to be launched.

A final point that is worth mentioning because it has been too often overlooked is that the high rate of decrease of ambient static pressure that occurs during the boost phase of flight require special attention to the venting of sea level air trapped in adapters, shrouds, external equipment bays, and exposed equipment.

Preflight Checkout

A significant lesson from the preflight checkout area is that equipment must not only be designed to operate, it must also be designed to be checked to verify that it is operating or ready to operate. Unless a great deal of thought is given at the design stage to the requirement for checking, we end up as we did in some cases in Mercury, with systems that cannot be checked without incurring the hazards that are always associated with breaking into plumbing and electrical circuits.

Future programs could profit from this experience by devoting increased effort at the design stage to location of equipment for servicing and easy removal, by providing adequate filling, draining, and flushing ports for fluid systems, with planned accessible pressure taps for preflight checking, and by increased attention to the design and location of electrical disconnect points.

Leaking and Sealing

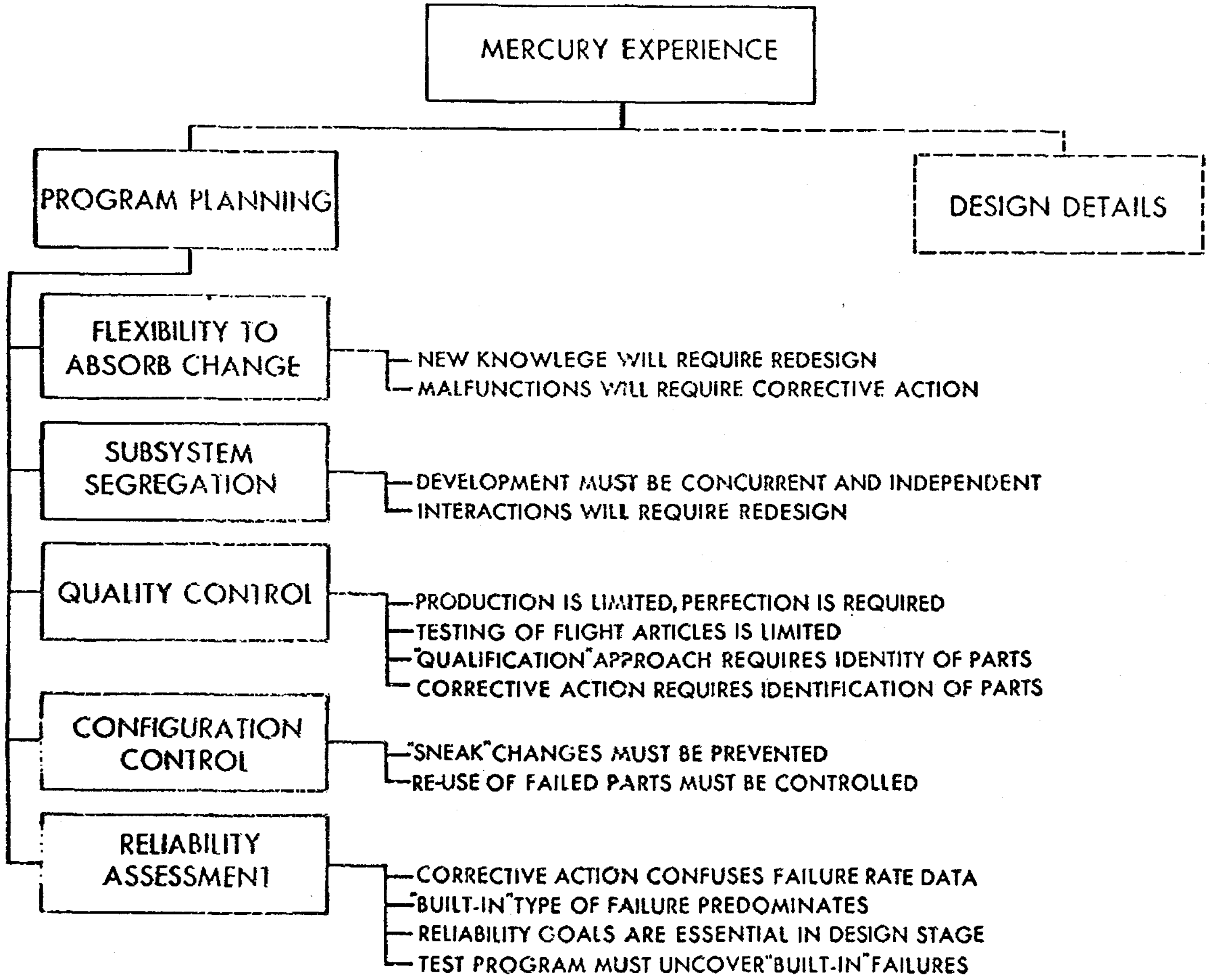
Another problem that has given a great deal of trouble in Mercury, and will demand even greater attention in future spacecraft, is the problem of leakage. The weight limitations of spacecraft tend to force the use of extremely high pressures in onboard gas systems. Components of these systems such as pressure regulators and shut-off valves have been particularly prone to leakage problems. In Mercury the hazardous character of any leakage from the reaction control fuel systems and the corrosiveness of the H_2O_2 fuel has made the assembly and maintaining of plumbing in this system a very serious problem. Not only have extreme measures been required to prevent leakage at joints in piping, but also, special provisions have had to be made to drain overboard any leakage that might occur past seals in valves.

Maintaining the gaseous atmosphere within the cabin itself is no simple problem. It greatly complicates the design of the hatches required for normal or emergency egress. The combined problem of leakage and weight attracts designers to use of explosive systems that merely blow off portions of the existing structure for emergency egress. The difficulty with this solution is the potential hazard of inadvertent actuation of the explosive either through human error or through some unforeseen environmental factor not covered during qualification tests. It is, of course, extremely difficult to duplicate in ground qualification tests the combined heating, vibration, and vacuum environmental history of a full scale explosive hatch on a deep-space mission.

Conclusion

In summary, the experience gained in the Mercury program has indicated a number of areas in both program planning and spacecraft design where additional measures beyond those adopted in Mercury are needed if we are to achieve the level of success or safety we want in the more sophisticated missions to come. These measures are being incorporated into future manned programs. The Mercury program to date has not uncovered any insurmountable technical problems that would block man's progress into space. This, perhaps, is its most important lesson.

RELIABILITY AND FLIGHT SAFETY LESSONS



MERCURY EXPERIENCE

PROGRAM PLANNING

DESIGN DETAILS

FLEXIBILITY TO ABSORB CHANGE
- NEW KNOWLEGE WILL REQUIRE REDESIGN
- MALFUNCTIONS WILL REQUIRE CORRECTIVE ACTION

SUBSYSTEM SEGREGATION
- DEVELOPMENT MUST BE CONCURRENT AND INDEPENDENT
- INTERACTIONS WILL REQUIRE REDESIGN

QUALITY CONTROL
- PRODUCTION IS LIMITED, PERFECTION IS REQUIRED
- TESTING OF FLIGHT ARTICLES IS LIMITED
- "QUALIFICATION" APPROACH REQUIRES IDENTITY OF PARTS
- CORRECTIVE ACTION REQUIRES IDENTIFICATION OF PARTS

CONFIGURATION CONTROL
- "SNEAK" CHANGES MUST BE PREVENTED
- RE-USE OF FAILED PARTS MUST BE CONTROLLED

RELIABILITY ASSESSMENT
- CORRECTIVE ACTION CONFUSES FAILURE RATE DATA
- "BUILT-IN" TYPE OF FAILURE PREDOMINATES
- RELIABILITY GOALS ARE ESSENTIAL IN DESIGN STAGE
- TEST PROGRAM MUST UNCOVER "BUILT-IN" FAILURES

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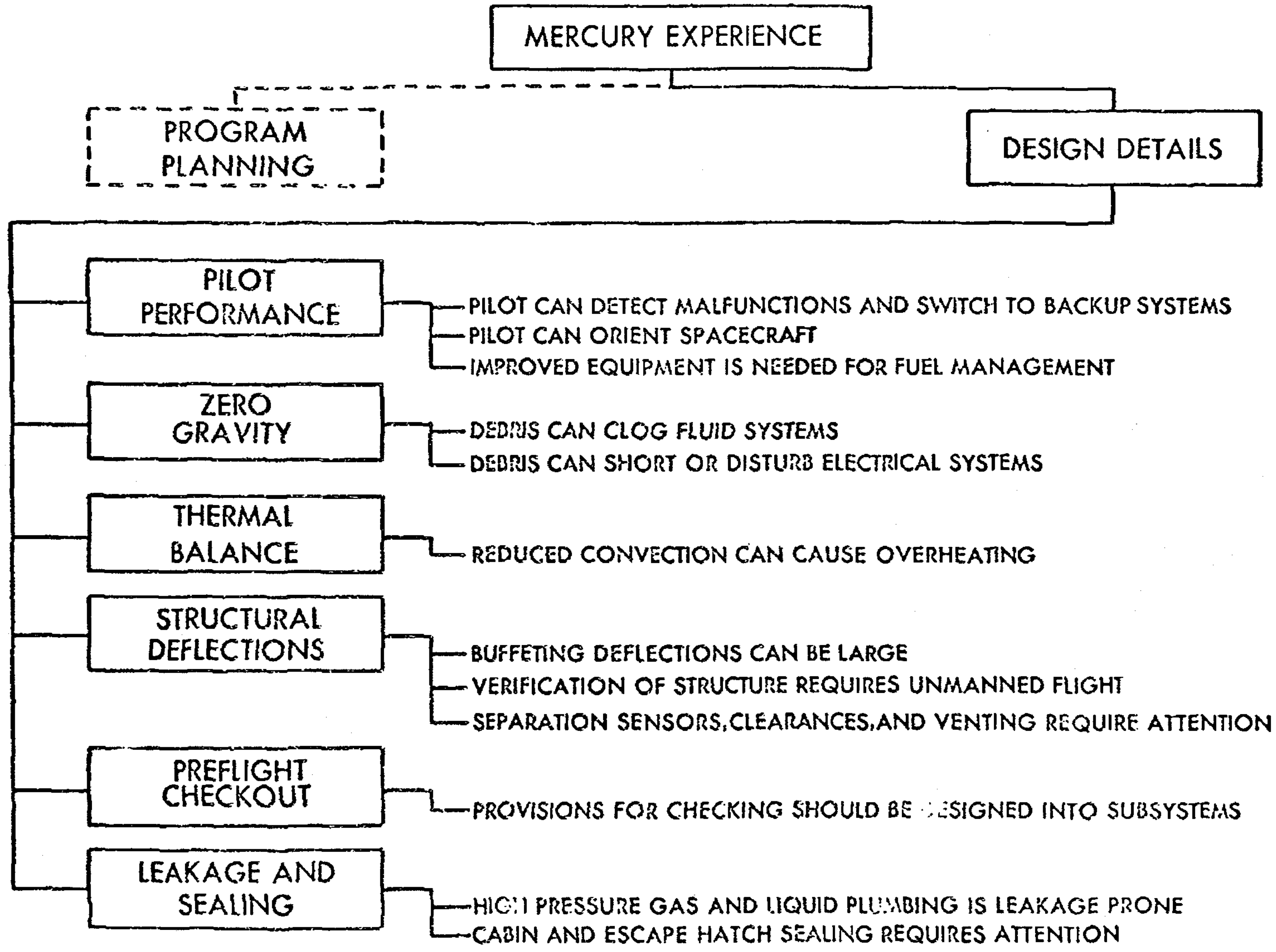
RELIABILITY AND FLIGHT SAFETY LESSONS



MERCURY EXPERIENCE

PROGRAM PLANNING

DESIGN DETAILS

PILOT PERFORMANCE
- PILOT CAN DETECT MALFUNCTIONS AND SWITCH TO BACKUP SYSTEMS
- PILOT CAN ORIENT SPACECRAFT
- IMPROVED EQUIPMENT IS NEEDED FOR FUEL MANAGEMENT

ZERO GRAVITY
- DEBRIS CAN CLOG FLUID SYSTEMS
- DEBRIS CAN SHORT OR DISTURB ELECTRICAL SYSTEMS

THERMAL BALANCE
- REDUCED CONVECTION CAN CAUSE OVERHEATING

STRUCTURAL DEFLECTIONS
- BUFFETING DEFLECTIONS CAN BE LARGE
- VERIFICATION OF STRUCTURE REQUIRES UNMANNED FLIGHT
- SEPARATION SENSORS, CLEARANCES, AND VENTING REQUIRE ATTENTION

PREFLIGHT CHECKOUT
- PROVISIONS FOR CHECKING SHOULD BE DESIGNED INTO SUBSYSTEMS

LEAKAGE AND SEALING
- HIGH PRESSURE GAS AND LIQUID PLUMBING IS LEAKAGE PRONE
- CABIN AND ESCAPE HATCH SEALING REQUIRES ATTENTION

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