COMPONENT PERFORMANCE AND FLIGHT OPERATIONS OF THE X-15 RESEARCH AIRPLANE PROGRAM

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Introduction

Commonly used methods of predicting reliability on the basis of failure testing and sampling techniques do not give a realistic picture of component performance under operational conditions. Simulated, controlled test conditions simply cannot accurately duplicate true operational environments.

The X-15 program has provided data on component performance while accomplishing research in hypersonic flight, sub-orbital flight, and piloted reentry environments. This paper discusses and analyzes the system and component failures that have occurred during the X-15 program. Component performance is expressed in terms of its effect upon the entire operation, that is, as a failure rate per flight. Three representative systems are discussed: the engine system, the auxiliary power system, and the propellant system. Failures of shelf-stock components prior to their installation on the flight vehicles are also examined.

Flight Operations

The X-15 program is conducted jointly by the U.S. Air Force and the National Aeronautics and Space Administration. Three X-15 vehicles are used in the program; two modified B-52 bombers serve as airborne launch platforms. For a typical flight, the X-15 is carried aloft and launched at 45,000 feet altitude after a one-half-hour cold soak. After launch, the X-15 rocket engine burns for 80 seconds, which accelerates the vehicle to 3400 miles per hour during the climb to 260,000 feet altitude. The latter portion of the climb and the reentry is a ballistic trajectory. Vehicle surface temperatures reach 1000° F during the 5g reentry. The pilot lands the X-15 at Edwards Air Force Base, Calif., 10 minutes after launch.

Although the X-15 program is considered a highly successful research project, in which 151 flights have been accomplished, progress has been hampered significantly by failures of components, as well as by other factors. Figure 1 shows the proportionate amount of delays caused by various factors, excluding routine maintenance and modification periods. In this program, a critical failure in any principal system prior to launch is considered cause for a flight abort.

As shown in the figure, weather has been the cause of most of the delays, followed by structures, which includes the landing gear. The miscellaneous category encompasses everything from a pilot's nosebleed to the inactive period preceding the decision to rebuild X-15 number 2. This inactive period, alone, accounted for over one-half of the delays in this category. Stability augmentation systems and inertial systems were problem areas early in the program, but extensive product improvement has reduced the failure ratio to a level that is now only a small proportion of the program delays shown in the figure. The engine system, auxiliary power system, and propellant system are examined in detail later in this paper.

Description of Vehicle

Figure 2 is a cutaway view of the X-15. An airflow-direction sensor, or "ball nose," constitutes the nose of the vehicle. Attitude control rockets are immediately aft of the ball nose and also in the wings. The cockpit is similar to, but slightly more complicated than, that of a modern single-engine military aircraft. The payload compartment contains experimental apparatus, data-recording equipment, and telemetry transmission equipment. The auxiliary power system furnishes electrical power, hydraulic power, and rocket fuel for the attitude control system. The major portion of the remaining fuselage is integral liquid-oxygen and anhydrous-ammonia propellant tanks. The aft fuselage contains the variable-thrust YLR99 rocket engine.

Figure 3 is a schematic drawing of the propellant and engine systems. The propellant system consists of a helium gas source that pressurizes the oxidizer and fuel tanks. The fuel and oxidizer are supplied to the engine by a high-speed turbine pump driven by decomposed hydrogen peroxide. The engine consists of a regeneratively cooled combustion-thrust chamber and a two-stage igniter, which furnishes continuous ignition. The propellant lines and combustion sections are automatically helium-purged each time the engine is shut down.

The auxiliary power system is made up of two independent auxiliary power units, each with its own pressurization and fuel supply for complete redundancy (fig. 4). Each power unit consists of a high-speed turbine connected by a gear train to an alternator and hydraulic pump. The turbine is driven by the decomposed hydrogen-peroxide fuel. The term "auxiliary power" is misleading, inasmuch as the unit furnishes all hydraulic and electrical power generated on the X-15. It is auxiliary only in the sense that it is not the primary thrust-producing system.

The design of the aircraft and the systems of the X-15 are described in detail by Mellinger[1] and Davis[2].

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Failure-Reporting Technique

Research data derived from flights is, of course, the objective of the X-15 program, and a flight with its preflight and postflight operations is considered to be one complete cycle of operation. A total of 138 flights was completed from March 10, 1959, to June 30, 1965; this number is used as the denominator for the failure ratios, except for the engine system. Failure ratios for the engine system are based on 117 flights, inasmuch as some of the early flights were made with an interim engine.

In this paper a failure is defined as a system malfunction that is considered unsafe for flight and includes any nonserviceable component condition. This condition may range from a suspected malfunction to an obvious failure. In either case, its effect on mission accomplishment is the same: the mission is delayed and manpower is required to correct the condition.

Failure rates for the X-15 are expressed in terms of the number per flight rather than the number of component operating hours, component operating cycles, or vehicle flight hours. The collection of data necessary to express failures in terms other than per flight is not practical for the X-15. The expenditure of manpower to determine, record, and maintain records of individual component operating cycles and/or operating time is a laborious task of questionable value in terms of the effect on flight operations.

The actual flight hours of the X-15 are only a fraction of the total operating time of the systems. For example, the average flight time of the X-15 is 9 1/2 minutes per flight, of which only 80 seconds is engine burning time. The total flight time for the period considered, March 1959 to June 1965, is about 22 hours for the airframes and about 2 1/2 hours for the engines. Expressing failures as rate per flight is considered to be valid in that it includes all operating characteristics, times, and environments, in addition to the human element.

In the X-15, as in any spacecraft system, the mix of parts is complex. Identical parts are used for different functions and in different systems, as well as in parallel or redundant systems. Parts from different manufacturers are used for the same function when they have similar operating characteristics. To provide a basis for comparison, failures for components of similar types or functions are combined to establish an equivalent number of failures per type of component. The failure rate reflects only the equivalent failures of each type of component. For more than one of the same component, the actual number of failures is a simple multiple. For example, 92 failures of 3 regulators of a similar type is 30.7 equivalent failures per type of component. The equivalent failures divided by the number of flights (138) is a failure rate of 0.222.

As implied, only active-type parts or components are considered in this discussion. Passive-type parts or components, or those with non-moving parts, such as lines, fittings, hoses, and wires, are not considered.

Component Performance

The engine, auxiliary power system, and propellant system of the X-15 were selected for examination because of their critical nature, the large number of failures experienced during the program, and because they are considered common to spacecraft vehicles.

The engine-system failure rates per flight are shown in figure 5. The most-failed component is the turbopump assembly, with 0.855 failure per flight. The engine is a relatively complex system. The 10 most-failed items represent 20 percent of the total system components. This 20 percent accounted for 70 percent of the total failures.

Figure 6 presents the failure rates of the 10 most-failed type of components in the auxiliary power system. The spring-loaded pressure-sensing switch has the highest rate of 0.330 failure per flight. This system has the least number of components; the 10 most-failed items represent 40 percent of the total; yet this 40 percent accounts for 70 percent of the total failures.

Figure 7 shows the propellant-system failure rate per flight of the nine most-failed type of components. A pneumatically operated vent and relief-type valve have the highest failure rate, 0.377 per flight. Again, components of these nine categories constitute 31 percent of the total system and account for 72 percent of the total failures.

It is significant to note that, in each system, even though complexity varies considerably, most failures are caused by a small number of components.

Failures per flight and average time between failures are compared in the following table for the most-failed component in each of the three systems as well as the system itself. The operating time per flight is a conservative estimate that includes ground run, bench check, servicing, prelaunch, and free-flight times. The range of average-time-between failure is 0.02 hour to 1.6 hours for the systems and 0.1 to 9 hours for the components, which is quite low for mechanical components.

Failures in the three systems have occurred in a continuous and random manner throughout the program. Figure 8 is a time profile of the most-failed item of each system considered, and figure 9 shows failures for the median-ranked items of the 10 most-failed items in each system.

These data indicate that, despite the long time period and large number of flights being considered, the anticipated effect of "smoothing out" the data has not been evident.

	Failures per flight	Flights per failure	Operating time per flight, hr	Average time between failures, hr
Components				
Turbopump	0.855	1.17	0.1	0.1
Spring pressure switch	.330	3.00	3	9
Pneumatic vent and relief valve	.377	2.65	3	8
Systems				
Engine	6.1	.16	.1	.02
Auxiliary power	3.7	.27	3	.8
Propellant	1.9	.53	3	1.6

Although the large number or consistency of failures shown in figures 5 to 9 might seem to imply otherwise, product improvement has been undertaken whenever a problem area has become evident. The appendix summarizes the product improvements for the most-failed item in each system.

In the X-15 program, an alarming number of failures occur, or are inherent, even before supposedly serviceable components are installed on the flight vehicle. Twenty to 26 percent of the reported failures have been consistently from shelf stock. The following table lists the failures or cause for rejection of items drawn from shelf stock for the 6-month period of December 1964 to June 1965. All components were new or refurbished.

The source of these failures, which are apparently universal in industry, became obvious after a change was made in the method of reporting failures. The type of failure varied from not performing in accordance with specification, which has been the largest category, to manufacturing error.

A high rejection rate of shelf stock was expected in the early phases of the program. However, until this year, when the new reporting system was implemented, the rate had not changed appreciably. Corrective action was taken as soon as this source of failure was documented. This action consisted, primarily, of bringing the situation to the attention of all concerned, since procedures in effect were adequate if enforced. Occasionally, shelf deterioration of parts due to exposure of corrosive material has required product improvement. In any event, the key to corrective action has been close cooperation between the manufacturer and the user. Industry and Government have taken similar action, with programs such as ZD (Zero Defects) and PRIDE (Personal Responsibility In Daily Efforts), to improve control of quality.

Conclusions

The X-15 research airplane program has demonstrated that a failure rate expressed as a rate per flight is a more realistic method of reporting component performance for experimental vehicle programs than the statistical sampling and failure distribution techniques in popular use. During the program, component failures have been more numerous than reliability predictions indicated. A small number of components have been responsible for most of the failures regardless of system

Category of rejection	Number of rejections	Percent of rejections
Performance out of specification tolerances	39	40
Improper identification or status	21	22
Misinterpretation of test specifications	11	12
Expiration of shelf life	9	9
Rough handling	5	5
Miscellaneous	5	5
Tested under nonoperational conditions	4	4
Improper packaging	3	3
Total	97	100

complexity. There has been no appreciable decrease of failures with time.

The program has also demonstrated that the industry-wide problem of excessive defects of shelf-stock components can be improved by close cooperation between the user and the manufacturer. This approach must include a realistic and timely method of reporting failures and a constant effort to impress individuals with the importance of their personal responsibility in handling components.

Appendix

Product Improvement

Considerable product improvement of components has been undertaken during the X-15 program. Improvements made in the most-failed item in each of the three systems are summarized here as examples.

The pneumatic vent and relief valve of the propellant system originally contained a diaphragm material that cracked upon repeated exposure to the ammonia environment. A new material was substituted that does not deteriorate, yet leakage problems still exist in the valve. It has been difficult to determine the exact cause of leakage so that further corrective action can be taken.

In the engine system the turbopump assembly has been a source of leakage as the result of seal deterioration and wear, despite frequent preventive maintenance. The corrosive nature of the fluids handled and the high-speed operation have created difficult sealing conditions. Because of the unavailability of any improved seals, the leakage specification was relaxed to increase the amount of allowable leakage. This was only an interim measure and permitted operation until adequate seals could be developed. A tandem, metal O-ring seal is now being evaluated and is expected to reduce the leakage considerably.

The pressure switch of the auxiliary power system has had three major modifications. Originally, the hydrogen peroxide reacted with the aluminum switch body to form contamination that prevented proper switch operation. The switch body material was changed to stainless steel. Soon after the contamination problem disappeared, diaphragm failures became apparent, caused by punctures of the diaphragm material by foreign objects. A new, stronger material was substituted and the problem was solved. Thirdly, corrosion of the switch actuating arms appeared and caused improper switch operation. The solution was to replate the arms with electroless nickel to resist the corrosion.

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1. Mellinger, G. R.: Design and Operation of the X-15 Hypersonic Research Airplane. AGARD Rep. 288, Oct. 1960.

2. Davies, Harold: The Design and Development of the Thiokol XLR99 Rocket Engine for the X-15 Aircraft. J. Royal Aeronautical Society, vol. 67, no. 626, Feb. 1963, pp. 79-91.

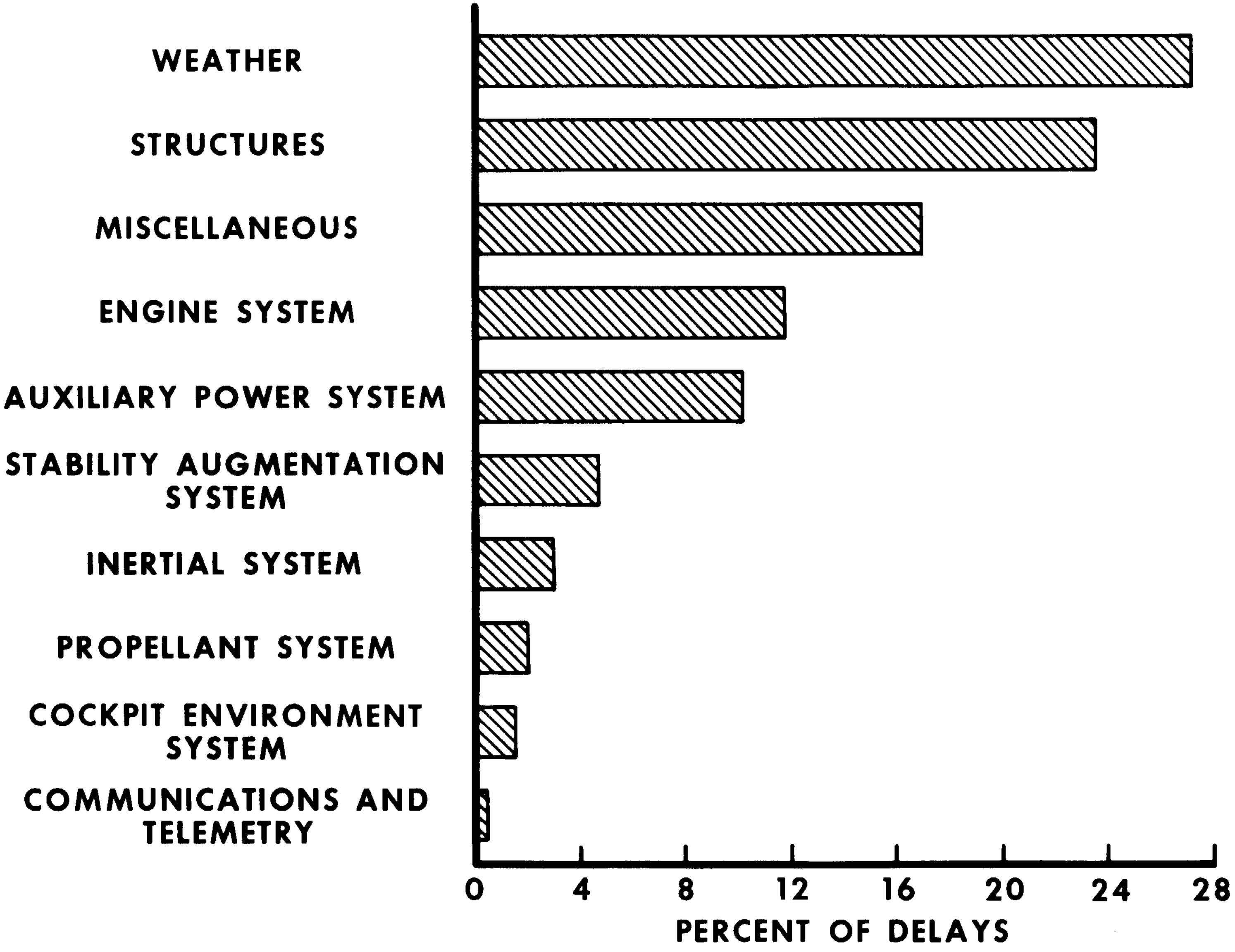

Figure 1.– Distribution of X-15 program delays - March 1959 through June 1965.

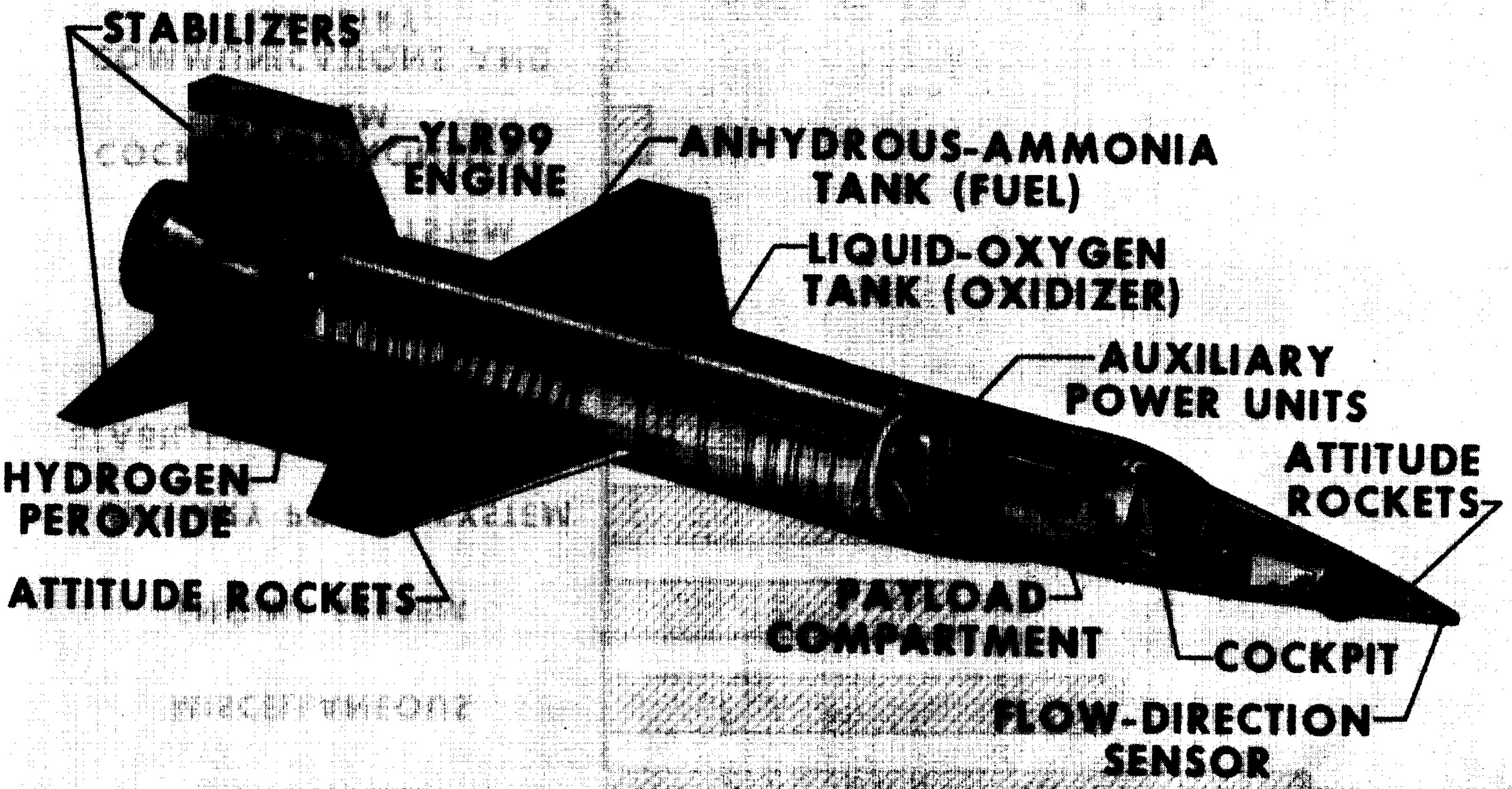

Figure 2.- Cutaway of X-15 airplane.

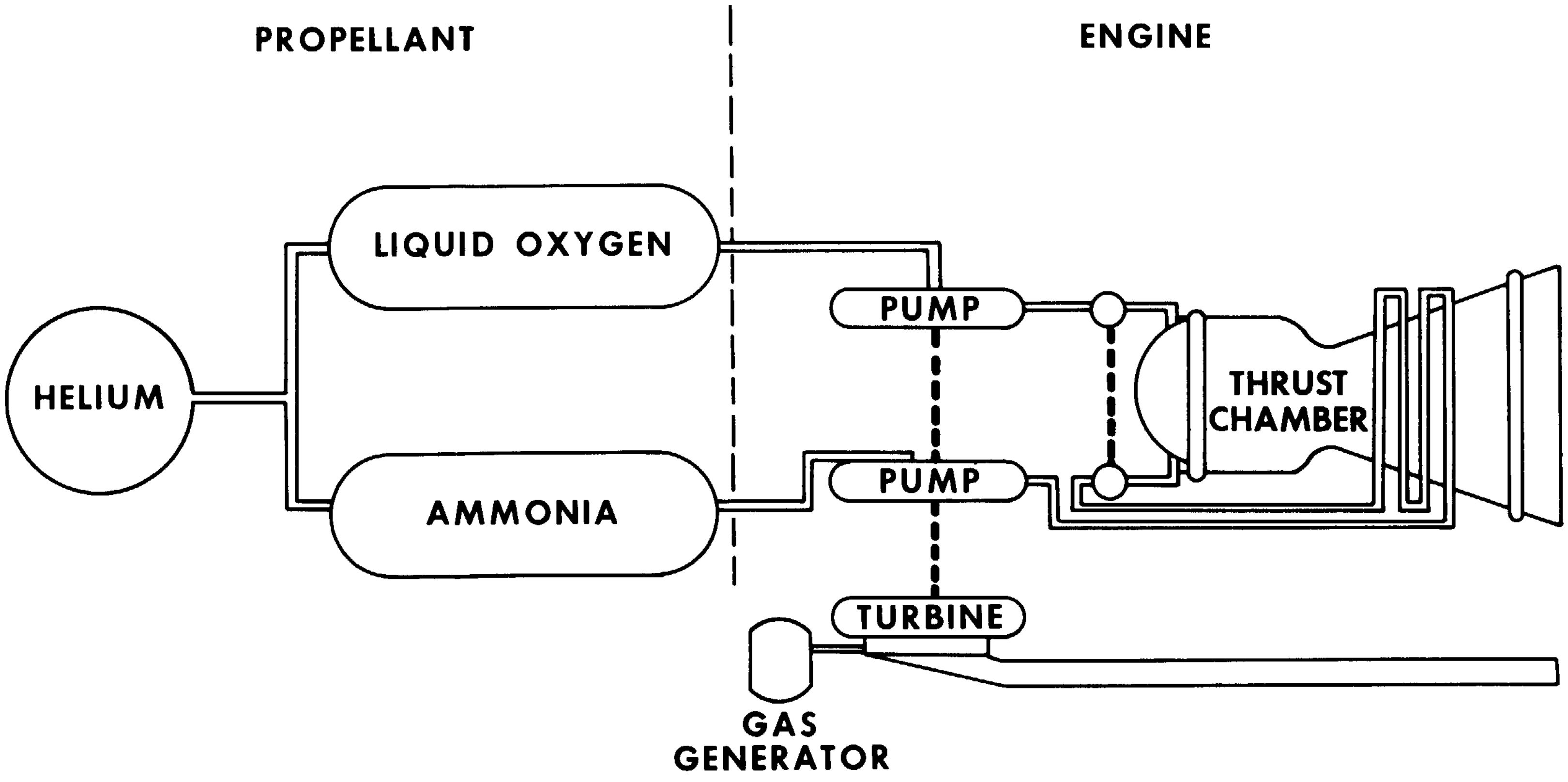

Figure 3.- Schematic of X-15 propellant and engine systems.

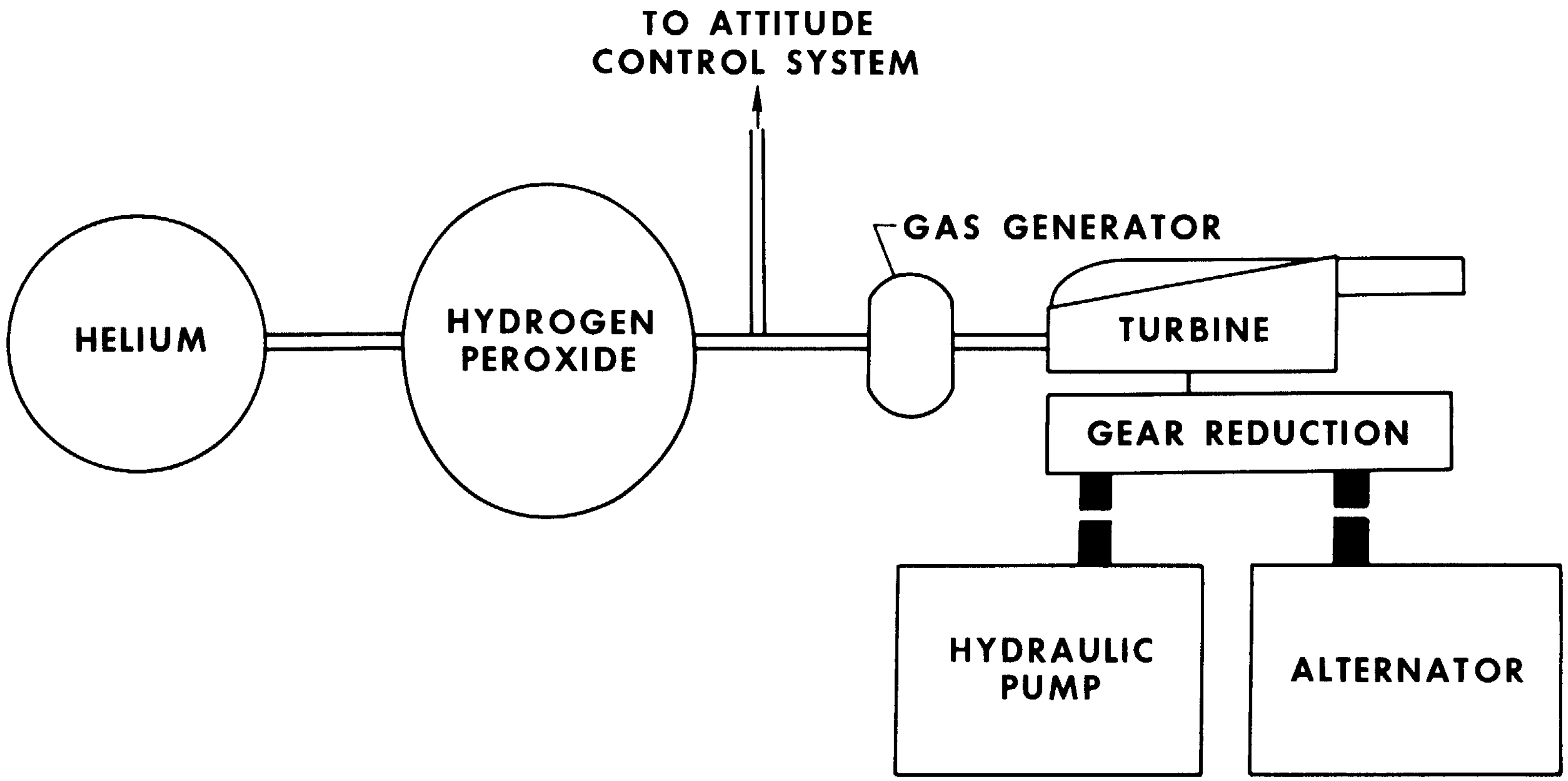

Figure 4.– Schematic of X-15 auxiliary power system.

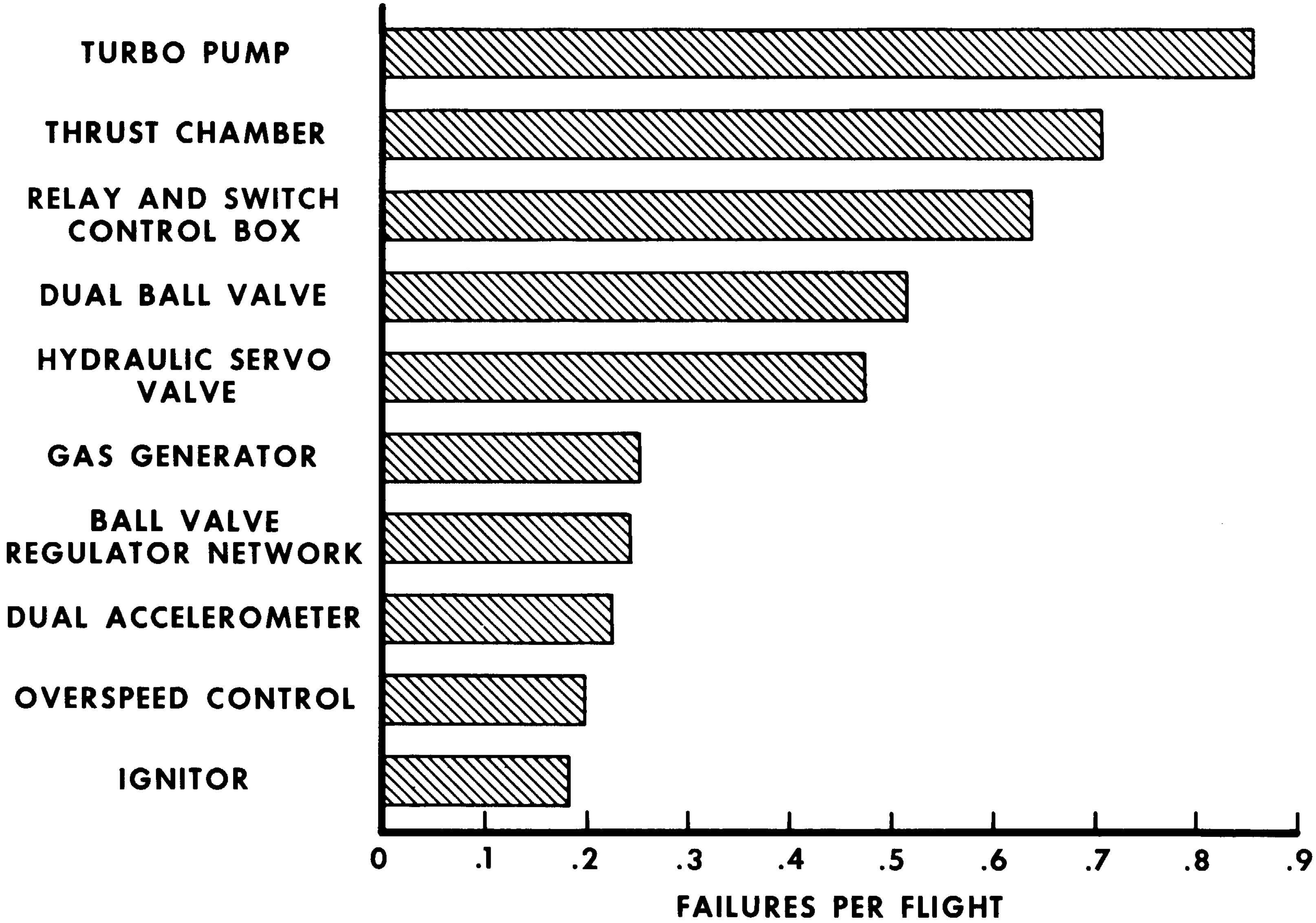

Figure 5.- Engine system component failure rate per flight.

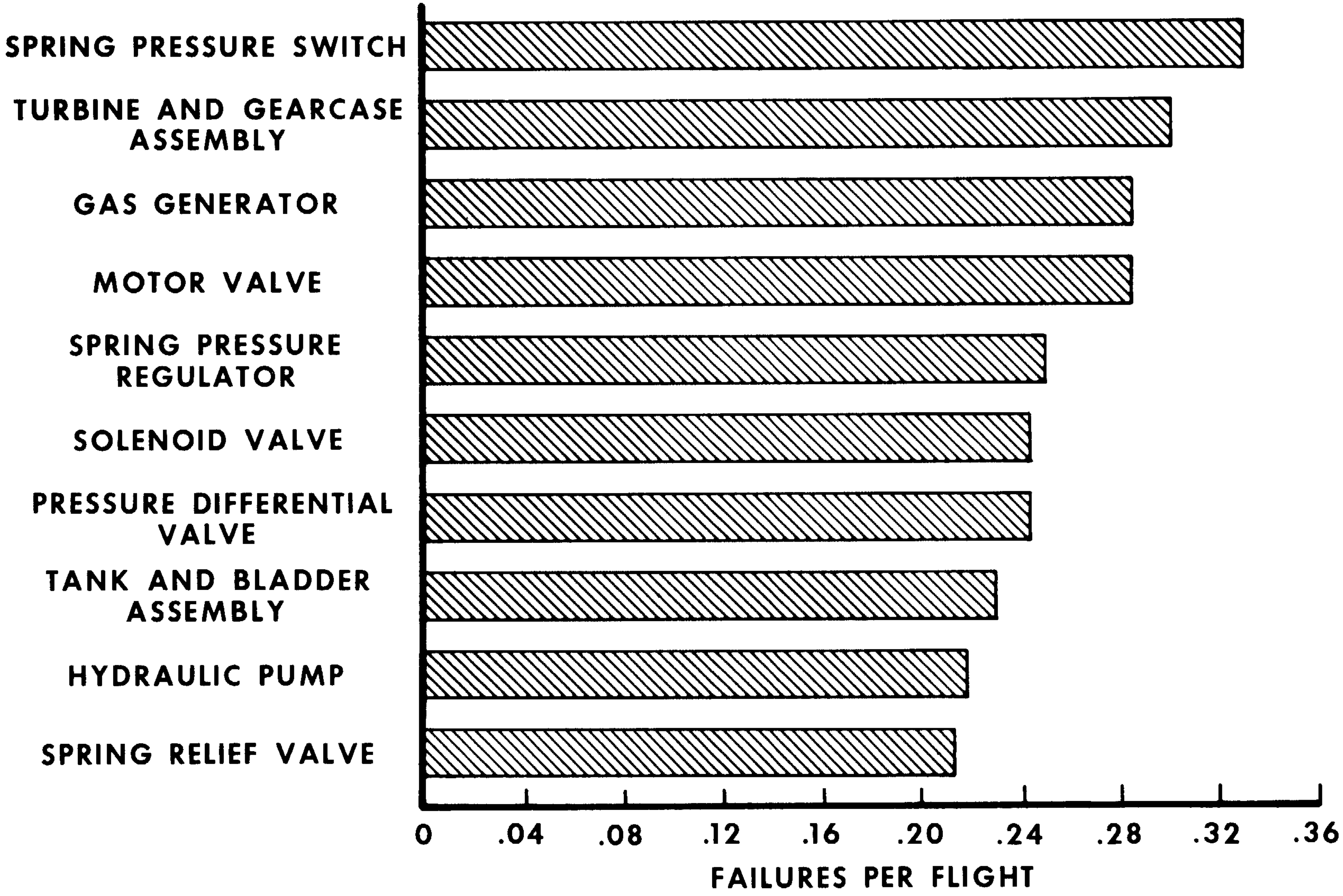

Figure 6.– Auxiliary power system component failure rate per flight.

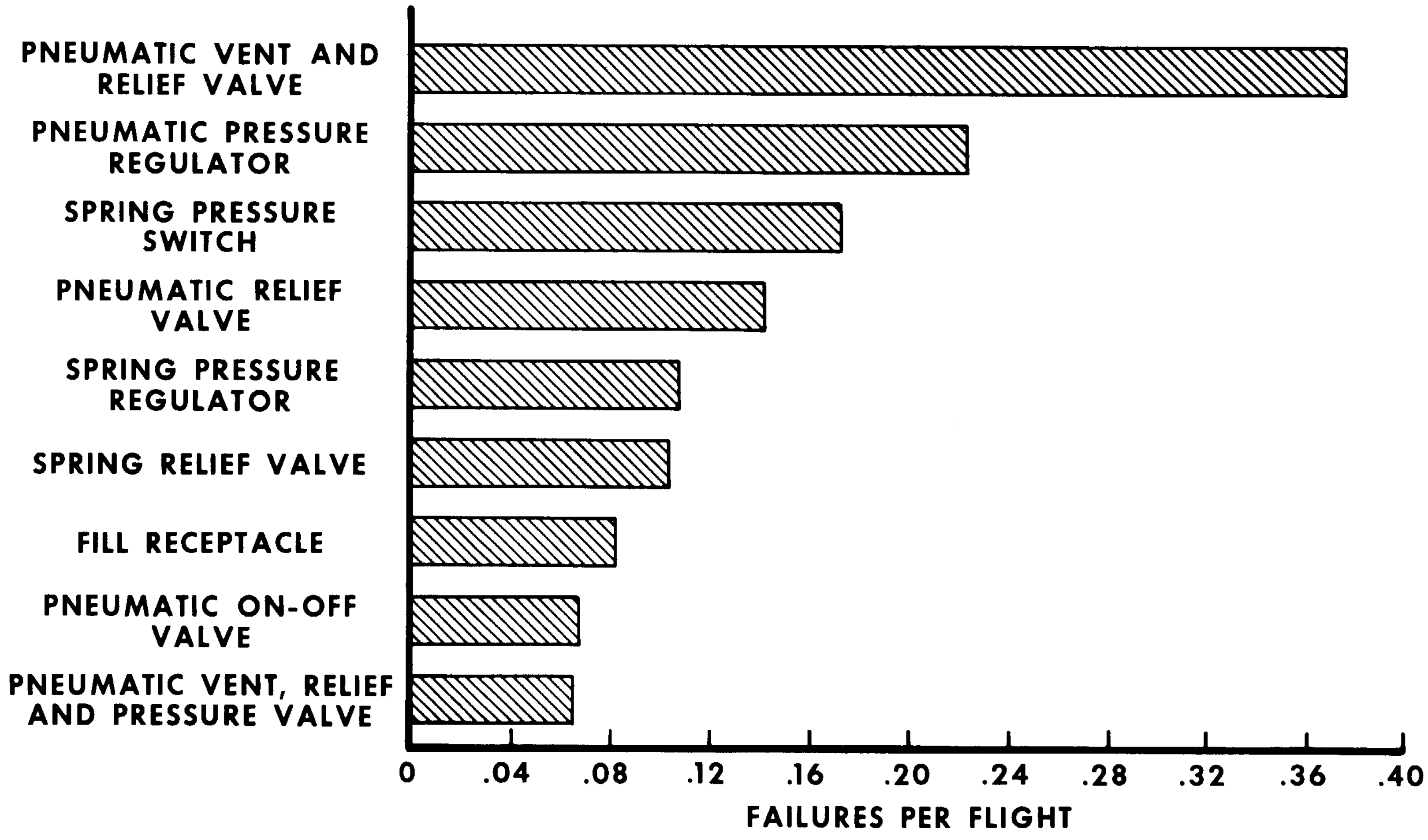

Figure 7.- Propellant system component failure rate per flight.

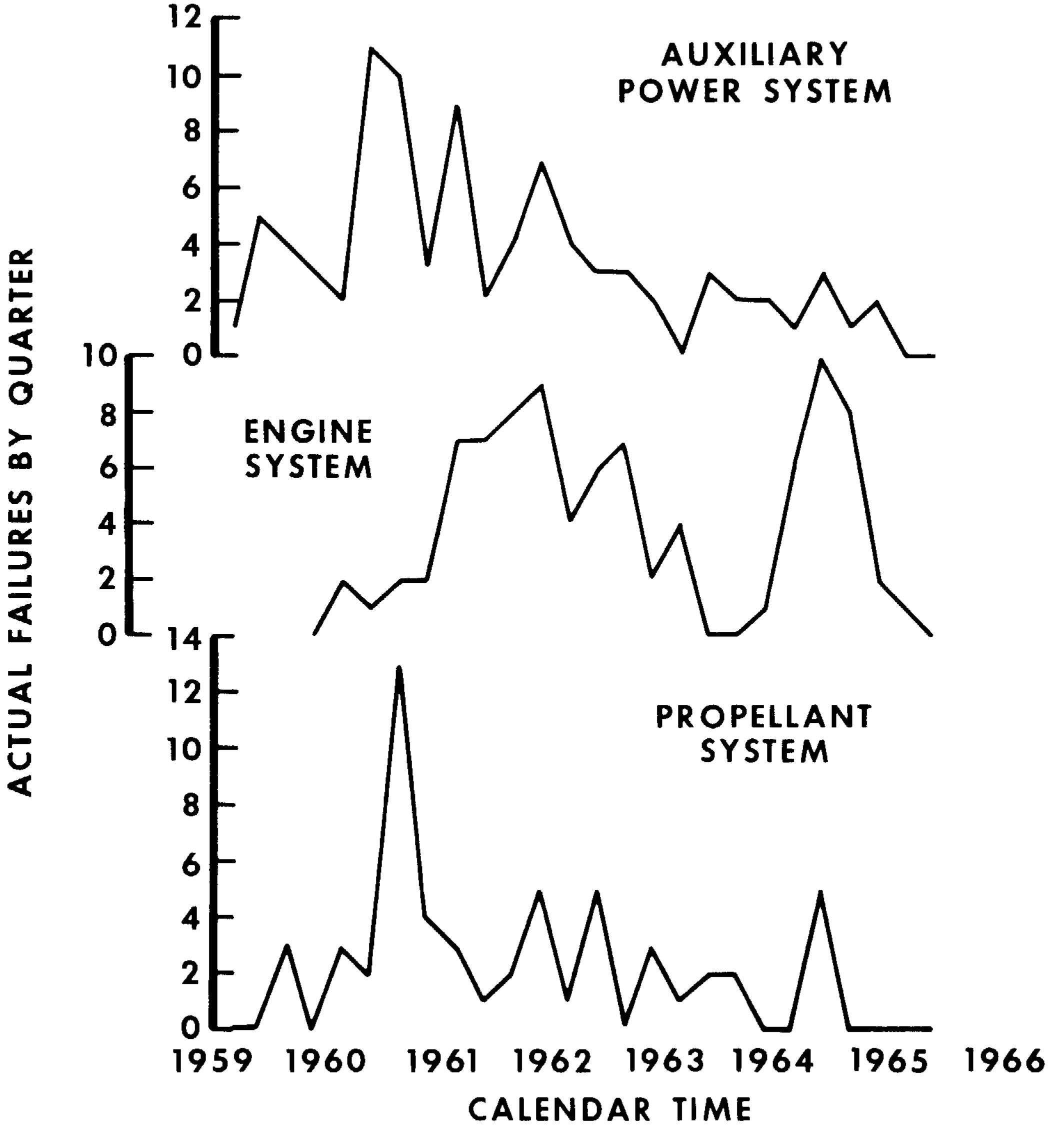

Figure 8.- Failure-time profile of most-failed items.

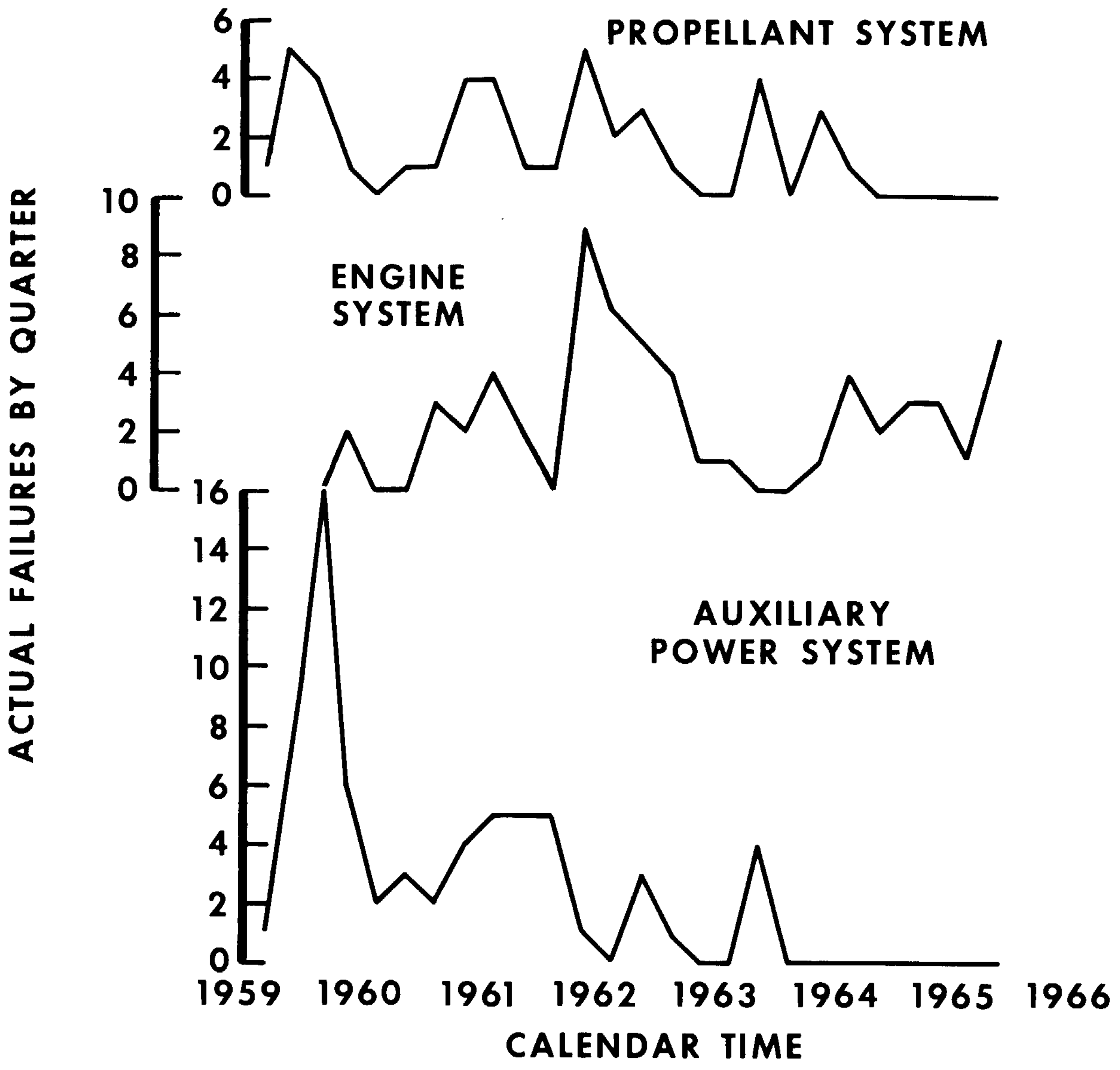

Figure 9.– Failure-time profile of median-ranked failed items.