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General Aviation Aircraft Reliability Study

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Executive Summary

This reliability study was performed in order to provide the aviation community with an estimate of Complex General Aviation (GA) Aircraft System reliability. To successfully improve the safety and reliability for the next generation of GA aircraft, a study of current GA aircraft attributes was prudent. This was accomplished by benchmarking the reliability of operational Complex GA Aircraft Systems. Specifically, Complex GA Aircraft System reliability was estimated using data obtained from the logbooks of a random sample of the Complex GA Aircraft population.

The approach used to estimate the current reliability of Complex GA Aircraft Systems included the following:

1. Define benchmark from population of GA aircraft (i.e., Complex GA Aircraft).
2. Define Complex GA Aircraft Systems.
3. Identify source of failure data.
4. State ground rules and assumptions.
5. Collect data for a random sample of Complex GA Aircraft population.
6. Analyze data to identify proper distribution that models failure data.
7. Perform goodness-of-fit and bias tests to validate distribution fit and verify sample randomness.
8. Estimate distribution parameters, system reliability, and system hazard rates.

The results of this analysis provide insight into the current reliability of Complex GA Aircraft Systems. All of the reliability estimates shown below were based on a six-hour flight. In addition, a ninety-five percent confidence was used to estimate the reliability of the Airframe, Electrical, Powerplant, Flight Control and Ground Control Systems. The Cockpit Instrumentation reliability estimate was performed in an earlier report that is included in Appendix A. All system Reliability estimates are as follows:

System	Reliability Estimate
Airframe	0.99940
Electrical	0.99997
Powerplant	0.99986
Flight Control	0.98476
Ground Control	0.99598
Cockpit Instrumentation	0.976

In this report, the Weibull distribution (two-parameter, β and α) was used to estimate Complex GA Aircraft System reliability. The goodness-of-fit tests and the bias tests performed indicate that the Weibull distribution best fits the aircraft data for these systems and that the sample used is not significantly biased. The results indicated that the random sample of aircraft used, along with the Weibull distribution, was appropriate for estimating the system reliabilities for the Complex GA Aircraft population.

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I. Introduction

This report presents the results of a study in which the current reliability of General Aviation (GA) Aircraft Systems was estimated. This report was prepared for the NASA Langley Research Facility's Office of Safety and Mission Assurance (OSMA). The results of this assessment provide insight into current general aviation reliability and may be used to assist in the development of future GA aircraft reliability and safety requirements.

II. Background

The current reliability of Complex GA Aircraft Systems is unknown. The ability to gain insight into this unknown will provide the aviation community with a valuable benchmark that will assist in the development of reliability and safety requirements for future aircraft. This benchmark must be established in order to ensure that technology development, design guidelines, and work on certification standards progresses towards the effective goal of affordable technologies for small single engine airplanes. This is a key issue to revitalizing the next generation of general aviation aircraft. The effect of a successful, safe, and reliable product will make general aviation aircraft in the United States accessible to a majority of the population. In order to meet this goal, insight into the current reliability of general aviation aircraft is required.

This report covers what is termed Complex GA Aircraft Systems and represents the compilation of several reliability studies involved with determining the reliability of these systems (i.e., Airframe, Cockpit Instrumentation, Control, Electrical, and Powerplant Systems).

III. Statement of Problem

The goal of this study was to assess the current reliability of Complex GA Aircraft Systems. In order to provide relevant information regarding GA aircraft reliability that is conducive to the engineering goal of ensuring development of an affordable, advanced single pilot transportation aircraft, it is necessary to include airplanes that share many of the characteristics of future aircraft design.

The proposed future aircraft design will consist of an aircraft with a cruise speed of 160 knots and a range of 700 nm. This aircraft is considered to be a single pilot, four-place, light-single engine piston aircraft with near all weather capability. Complex GA Aircraft have retractable landing gear, flaps, and a constant-speed propeller. The systems of the future aircraft will be very similar to current Complex GA Aircraft Systems and therefore, represent the population of GA aircraft used in this study. Where the futuristic airplane model did not provide guidance into design complexity or definition, typical Complex GA Aircraft architecture was assumed.

IV. Approach

The approach used in performing the reliability study was to define the Complex GA Aircraft Systems and Subsystems for complex aircraft, collect failure data from a random sample of complex aircraft, and then analyze the data in order to determine reliability estimates. To accomplish this, Complex GA Aircraft were divided into the following five systems indicating primary function:

Airframe - *any component or structure that is essential to the structural integrity of the aircraft. Even though they aren't considered part of the structural integrity of the aircraft, the interior upholstery, the aircraft paint and the static wicks are also part of the Airframe System.*

Cockpit Instrumentation - *the minimum instrumentation required for general aviation aircraft flying under IFR conditions as defined in Federal Aviation Regulations (FAR) Part-91 (see Appendix A).*

Control - *any component that controls the aircraft's attitude, heading, and altitude or changes the aerodynamic characteristics of the aircraft in the air or on the ground (excluding powerplant). This system is composed of two primary systems, Flight Control and Ground Control.*

Electrical - *the lighting system and any components involved in the source and distribution of electrical power.*

Powerplant - *any component or system that is essential to developing thrust for the aircraft. (The only exception to this is the inclusion of the heating and ventilation system under Powerplant).*

The subsystems were also delineated by function; that is, a system performs a single independent function. The following sections describe the subsystems and the process in detail with the exception of the Cockpit Instrumentation System. The report and methodology used to estimate the reliability of the Cockpit Instrumentation System is found in Appendix A.

A. Airframe System

1. Wing

The Wing subsystem is any component or structure that is part of the wing, the fuselage carry-through, or any structure that directly supports the wing (i.e. wing struts). This does not include the control surfaces on the trailing portion of the wing or any components or structures that are SOLELY utilized by the fuel system (See Figure 1).

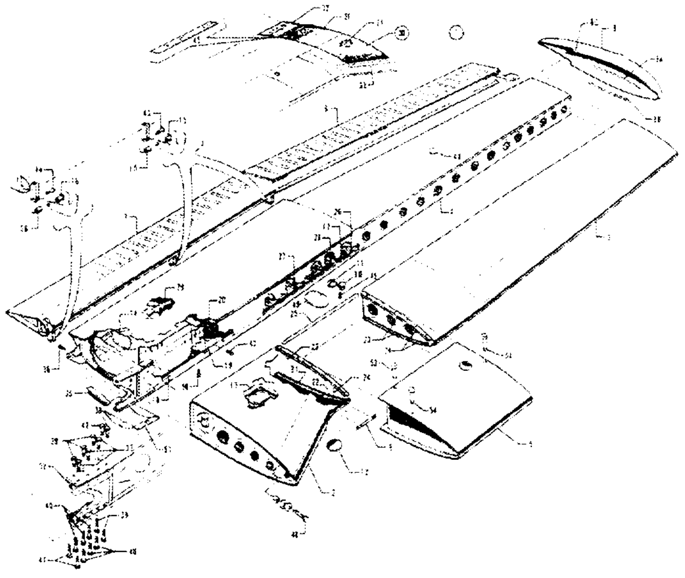


FIGURE 1 – EXPLODED WING DIAGRAM

2. *Empennage*

The empennage is any fixed part of the airframe that is aft of the last row of seats. This includes the baggage compartment, the tail cone and any fixed tail surfaces. The movable control surfaces are part of the Aircraft Control System.

3. *Cabin Fuselage including Engine Structure*

The fuselage is considered to be any component or structure that contributes to the structural integrity of the aircraft forward of the last row of seats and is not considered part of the wing subsystem. It includes the doors, engine mount and cowling, and the windshields and windows, instrument panel shock mount, and any other miscellaneous structure not associated with the wing subsystem.

4. *Upholstery*

This subsystem is mainly concerned with the furnishings in the cabin (carpet, trim, etc.). All components in this subsystem are considered non-structural.

5. *Seats*

The seats subsystem concerns any component that connects the pilot, co-pilot, or passengers to the airframe. This includes any component that is a part of the pilot's, co-pilot's, and passenger's seat or any supporting components such as the seat rails, the seat belts, and any adjustment mechanisms.

6. *Electro-Static Discharge (ESD)*

The ESD system on most aircraft is simply just the system of static wicks placed about the airframe. A static wick is a small flexible device that dissipates the static charge that often accumulates on an aluminum airframe traveling through charged air. This discharge effectively increases the transmitting and receiving range of the aircraft's electronics and also reduces the risk of a lightning strike (See Figure 2).

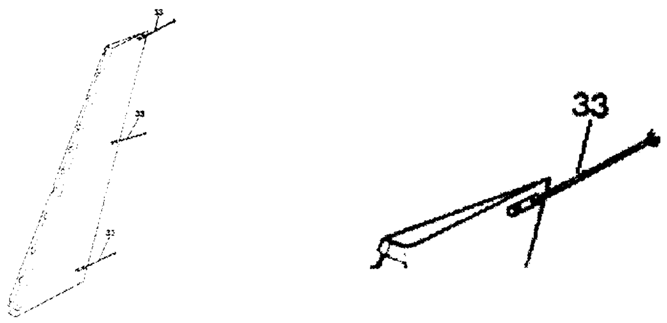


Figure 2 – Static Wicks (#33) on the Rudder (Cessna 210 Illustrated Parts Manual[1])

7. *Exterior Coatings*

This system concerns all paints, lacquers, or inhibitors applied to the exterior skin of the aircraft. These coatings usually serve a dual purpose; they serve to protect the skin from abrasive elements such as dust or corrosion, and they also serve an aesthetic purpose.

B. Flight Control System

The Flight Control System (FCS) of most Complex GA Aircraft is made up of six independent subsystems: longitudinal control, lateral control, directional control, flaps, trim, and at least a single-axis autopilot and are remarkably similar to the proposed future aircraft design. With the exception of Mooney aircraft, most complex aircraft have a relatively simple cable-operated system. The aircraft flaps are mostly electrically operated and are assumed to be of the Fowler-type. The longitudinal, lateral, and directional control system are mostly cable-operated utilizing bellcranks and push-pull rods; however, data was collected on the entirely push-pull rod systems, specifically those employed on Mooney aircraft.

1. Longitudinal Control System

A control column connected to a cable operates the longitudinal control system. The elevator/stabilator cable operates, through a series of pulleys, a bellcrank at the rear of the plane. This bellcrank is attached to the elevator spar, which then rotates the elevator/stablilator (See Figure 3).

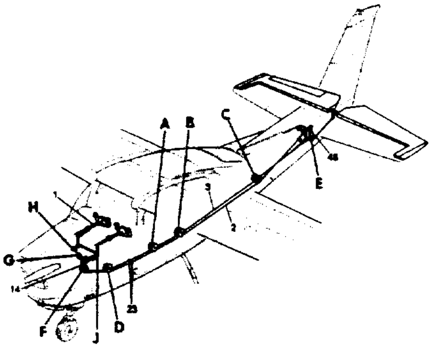


FIGURE 3 – DIAGRAM OF A TYPICAL LONGITUDINAL CONTROL SYSTEM (CESSNA 210 ILLUSTRATED PARTS MANUAL[1])

2. Lateral Control System

The lateral control system is similar in its operation to the longitudinal control system. The control column is again connected to a cable, which through a series of pulleys is connected to a bellcrank in each wingtip. The bellcrank operates a push-pull rod that moves the actual surface (See Figure 4).

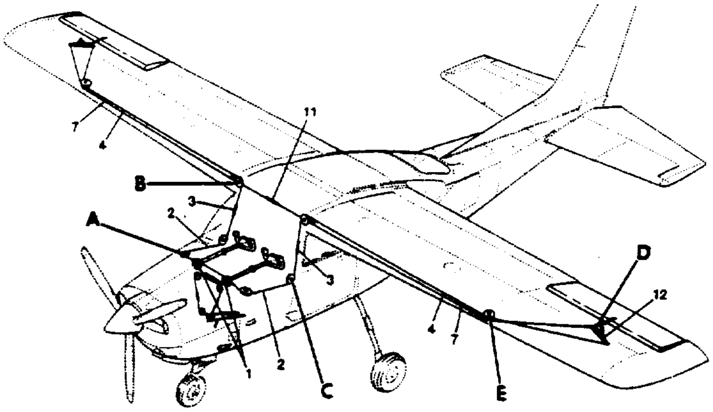


FIGURE 4 – DIAGRAM OF A TYPICAL LATERAL CONTROL SYSTEM (CESSNA 210 ILLUSTRATED PARTS MANUAL[1])

3. *Directional Control System*

The directional control systems in most aircraft are very akin to each other as well. The rudder pedals actuate a cable that, through a series of pulleys, operates a bellcrank at the base of the rudder (See Figure 5).

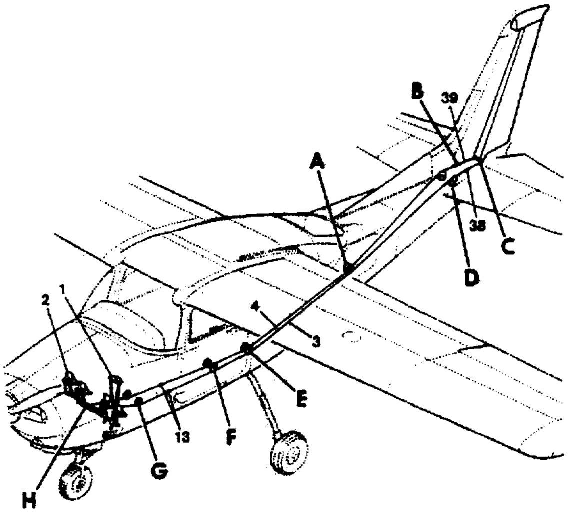


Figure 5 – Diagram of a typical directional control system (Cessna 210 Illustrated Parts Manual[1])

4. *Flap system*

The flap system on most aircraft is electrically operated. There is a control switch in the cockpit that actuates an electric motor, usually connected to a jackscrew that moves a push-pull rod connected to the flap. There is a cable system that connects the two flaps together and insures synchronized operation.

5. *Trim system*

The aircraft covered in this study have, for the most part, electrically actuated pitch trim. The system is mainly composed of a electric trim switch, usually located on the yoke or the instrument panel, that leads through a circuit breaker to an electric actuator in the tail or belly of the aircraft. This actuator moves either the cables associated with a trim tab/stabilator, or powers the surface directly.

6. *Basic autopilot*

The basic autopilot is a single-axis system consisting of a main frame, directional gyro, pitch and altitude sensing units, accelerometer, solid state pressure transducer, and servo actuators. This type of system is designed to function as a wing leveler, that is; it keeps the wings level, preventing the aircraft from banking either right or left.

C. Ground Control System

The Ground Control System (GCS) includes any system of the aircraft that control the airplane's heading and speed on the ground, excluding the power plant. Since the future will bring retractable landing gear into more aircraft, it is desirable to include the reliability of current retractable landing gear rather than fixed gear. For our study, on a Complex GA Aircraft, the ground control system consists of three subsystems; the landing gear (including the cockpit switches); the hydraulic system (that includes the brakes); and the ground steering system (defined to include components from the pedals to the steering boots).

1. Landing Gear

The landing gear subsystem includes all structure that is exclusively used by the landing gear, the wheels, the tires, and all associated switches, controls, or systems for extending and retracting the gear. On some aircraft, the extension and retraction of the gear also invokes a hydraulic system. However, this is usually an independent system and will be treated as such.

2. Hydraulic System

The hydraulic system includes all hoses, joints, and reservoirs associated with providing hydraulic pressure to the brakes, the brakes themselves, the brake pedals, and the parking brake assembly.

3. Ground Steering System

The ground steering system includes the rudder pedals, any associated rods that connect the rudder pedals to the nose gear, and the steering collar on the nose gear itself (See Figure 6).

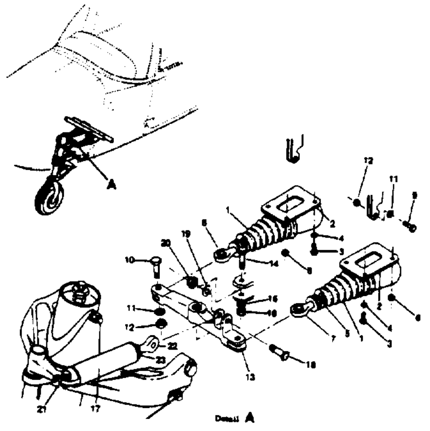


FIGURE 6 – GROUND STEERING SYSTEM FOR THE CESSNA 210 (CESSNA 210 ILLUSTRATED PARTS MANUAL)

D. Electrical System

1. Lighting

The lighting system is comprised of all light fixtures and their immediate components on the aircraft. The break point is any component whose sole purpose is to provide electricity to a light fixture. Any other wires or power packs that power more than just lights are part of the Source and Distribution System.

2. Source and Distribution

The Source and Distribution system includes any component that is involved in producing or providing electrical power to systems on the aircraft. This includes the battery, the alternator, and any wiring that is common to more than one system. If wiring or power packs are exclusive to a particular subsystem, such as the hydraulic power pack, it is not considered part of the Source and Distribution system.

E. Powerplant System

1. Engine

The engine subsystem contains all components that are strictly part of the aircraft's engine. This includes all the elements of the engine block and exhaust system including the magnetos. However, the alternator and engine-driven fuel pump are not included; those components go in the electrical system and fuel subsystem, respectively. The crankshaft is included, however, the constant-speed mechanism in the propeller is the cut-point between the propeller and engine subsystems (See Figure 7).

FIGURE 7 – CESSNA 210 ENGINE (CONTINENTAL IO-520)[1]

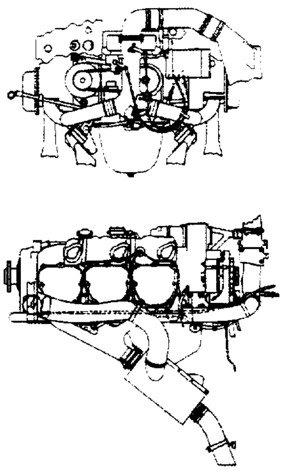
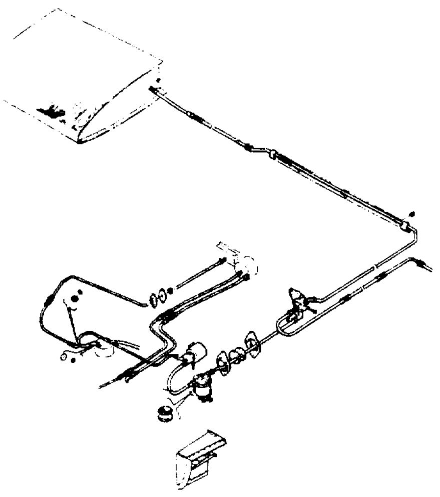


FIGURE 8 – PIPER PA-28R-201 FUEL SYSTEM



2. *Fuel*

The fuel system includes any component that contributes to providing fuel through the engine-driven fuel pump. This includes any fuel tanks (if integral, they were included in both airframe and fuel systems), and fuel tank related equipment in the tanks (e.g. sumps) except for any fuel quantity transmitting equipment. It includes any fuel lines, fuel cutoff switches, fuel filters, tank switches, and fuel boost pumps (including the on/off switch) (See Figure 8 above).

3. *Heating and Ventilation*

The heating and ventilation system incorporates all elements that control the temperature or the flow of air in the passenger cabin. This subsystem includes all scat tubes leading from the engine or exhaust systems, outside air vent and their respective plumbing, and the cockpit controls to regulate the temperature. However, while some of the aircraft in the sample were equipped with air-conditioning, these components were not considered part of the "typical" aircraft and therefore not included in this analysis (See Figure 9).

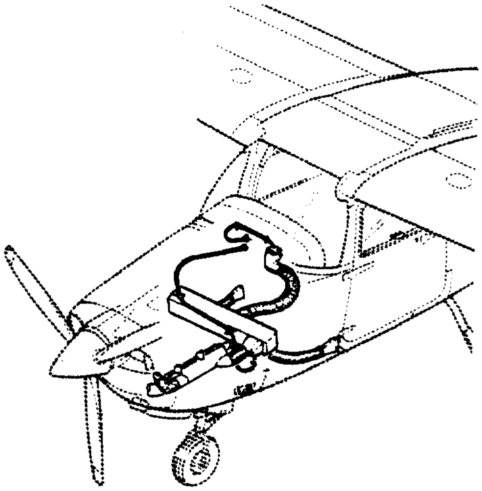


FIGURE 9 – HEATING AND VENTILATION SYSTEM FOR A CESSNA 210[1]

4. *Propeller*

The propeller includes any components that are involved in translating the engine's torque into thrust. This includes the pitch control mechanism, the spinner, the propeller itself, and any attachment hardware.

F. Data Collection

In order to determine the reliability of Complex GA Aircraft Systems, a method of collecting failure data was required. A particular note of interest is that estimating the reliability of a single aircraft manufacturer or specific type was not the intent of this study. Rather, estimating the current reliability of Complex GA Aircraft Systems in general was specified. After researching many data sources and collection methods, it was determined that failure data obtained from operational aircraft would provide a good benchmark of current system reliability and that logbooks of complex aircraft could provide the source of this failure data. The logbooks, required by law to be kept by aircraft owners, are reviewed by the Federal Aviation Administration (FAA) and cover the history of maintenance performed on the aircraft. Work performed on the aircraft is logged in these books and is signed by the mechanic who performed the work. This provides a good source of historical data regarding airplane component failures and replacements. It is also important to note at this time that "catastrophic failures" are not included in these records for obvious reasons and are not considered in this report.

The next step was to sample the population of Complex GA Aircraft. There are ways of assuring that the selection of a sample is indeed a random sample. Ideally, each item in a population would have the equal probability of being selected. In the sampling of Complex GA Aircraft this would entail identifying and including every aircraft ever built that fits the definition of a Complex GA Aircraft. Even if every aircraft that fits this description could be included, owner participation would have to be guaranteed. This was found to be unachievable. In addition, any aircraft randomly selected may have been involved in a catastrophic accident. In this case, legal methods may have been required in order to obtain aircraft documentation. In situations like these, a relatively haphazard selection method may be invoked, if it is believed that this method will not seriously violate the assumption of randomness[2]. The method used to obtain a random sample of the Complex GA Aircraft population is described below.

The random sample used for data collection was obtained by contacting flight schools and aircraft owners, and aircraft associations. In all cases it was made clear that any data obtained would be collected in confidentiality and that aircraft numbers, owner names, and specific aircraft failures would not be divulged beyond those individuals collecting the data. Flight schools were called directly and for practical purposes consisted mostly of local flight schools. However, data was also collected from flight schools outside of the local area and by door-to-door contact. By contacting aircraft owner associations, members were solicited from the head of the association directly in a newsletter. This provided all members with the opportunity to participate in the study while broadcasting this request nationwide.

To summarize, it was not known whether members would participate or not - nor was it known which complex aircraft would be included or how many aircraft would be obtained from each source. Through this relatively haphazard selection method of data collection defined above, it was believed that a random sample representative of the

Complex GA Aircraft population was obtained and was shown to be the case in Sections V.A., V.B., V.D., and VE.

1 Ground Rules and Assumptions

As in any analysis, no two individuals will perform a specific analysis identically (e.g., Fault Tree). The following ground rules and assumptions are defined so that a knowledgeable person can reproduce the results presented in this study. They identify constraints placed on the process allowing an accurate estimate of Complex GA Aircraft reliability, which is the primary purpose of this study. They also define failure, isolate factors from the analysis that may obscure hardware failure, and aid in simplifying the analysis. Although no two analysts will perform an analysis the same way, it is believed that the basic ground rules and assumptions used would not grossly deviate from those presented here. In this analysis, failure occurs when the inherent ability of a component to perform its intended function is lost and therefore could lead to a loss of an aircraft's system/subsystem function. Another way to look at failure for this analysis is any component failure that places the aircraft and pilot in a state of "elevated risk." Based on this concept, there were a number of ground rules and assumptions made to facilitate the collection of data and the accuracy of the results. These include:

- ✓ Only deal with "failures", not mandatory preventative maintenance or minor repairs where no components were replaced, examples are:

  1. Using the method of "stop-drilling," (i.e., drilling a hole at the end of a crack to remove stress, thus preventing additional crack propagation along the initial path) for a cracked fairing, would not be considered a failure until the fairing was replaced
  2. Replacing tires due to low tread or wear is not a "failure"; however, if the tires explodes or goes flat while in flight operations, then it is considered a failure
  3. An oil change is considered preventative maintenance and is not included
  4. Servicing of a battery.

- ✓ Bushings, shims, or components whose function is to wear, are not considered failures

- ✓ Regularly replaced items, those meant to wear and/or fail after a certain period of time, (i.e. lightbulbs, bushings, etc.) are not included in the analysis.

- ✓ No turbo-related components

- ✓ Any probes, gauges, or transmitters whose purpose is to provide information to the pilot are not included in this system. (This also includes the vacuum system.)

- ✓ Failures due to an improper part are not included

- ✓ Human induced failures are not included
- ✓ Missing parts are not considered failures (e.g., rivets, screws, bolts)
- ✓ Anything below the subsystem level is considered to be in series
- ✓ Failure/replacement due to mechanic's poor skills/procedures not included
- ✓ All systems are independent (i.e., loss of one subsystem does not result in loss of another subsystem function).

G. Data Analysis

The method selected for estimating the reliability of the GA Aircraft Systems was to first determine the proper distribution that models the collected failure data for each subsystem. This was accomplished by placing the failure data collected from the total number of aircraft sampled into a database and separating them according to the defined subsystems. By constructing probability plots (See Section V.C.2.) for each subsystem, distributions that describe the failure process can then be obtained. This information can then be used to determine the distribution parameters and identify confidence bounds. This method was preferred for several reasons. First, the data collected from the random sampling may not provide enough information to determine failure rates for each system component. Second, searching for generic component data, many of which are specialty items specific to a single aircraft type, would be very time consuming and costly. Finally, the fact that there are a number of Complex GA Aircraft from which, random sampling will probably yield a variation of aircraft types. Results of this effort are found throughout Section V., as well as in the various appendices.

Reliability Block Diagrams were developed in order to determine the reliability of each subsystem and system. As stated in the assumptions, each defined system and subsystem will be considered independent and failures of components within each independent.

Finally, the data collected was analyzed to determine how well the sample represents the Complex GA Aircraft population. The initial desire included that the results of the analysis would be able to provide a result that would have at most, a maximum error of the estimate of one order of magnitude. The error estimate was determined assuming a normal distribution in order to simplify the calculations. The results are presented in Section V.H.

V. Results

A. Aircraft

The failure data collected from the total number of aircraft randomly sampled was placed in a database and separated according to the pre-defined systems and subsystems. The total number of aircraft sampled and included in this report was thirty-three. This number was comprised of aircraft data from the various types of aircraft identified in Table 1. Note that a few of the aircraft sampled are not complex, however in four of the five systems analyzed (i.e., Airframe, Electrical, Powerplant, and Flight Control Systems) the systems of a non-complex aircraft are very similar to that of a complex aircraft. The only exception occurs in analysis of the Ground Control System. In this special case, data from these non-complex aircraft were not used.

Quantity	Manufacturer	Type
9	Mooney	M20 (8-J and 1-K)
5	Piper	PA-28R (One Turbo)
2	Cessna	177RG Cardinal
1	Cessna	172RG
1	Beech	A36
3	Cessna	T210 Centurion
3	Piper	PA-32R Saratoga (One Turbo)
3	Cessna	C-152
3	Cessna	C-172
2	Diamond	DA20 Katana
1	Cessna	182L

Table 1: Aircraft Type

B. Age

The following histogram provides insight into the age distribution of the aircraft sampled (See Figure 10). The heights of the rectangles indicate frequency of occurrence while the solid line depicts the cumulative frequency.

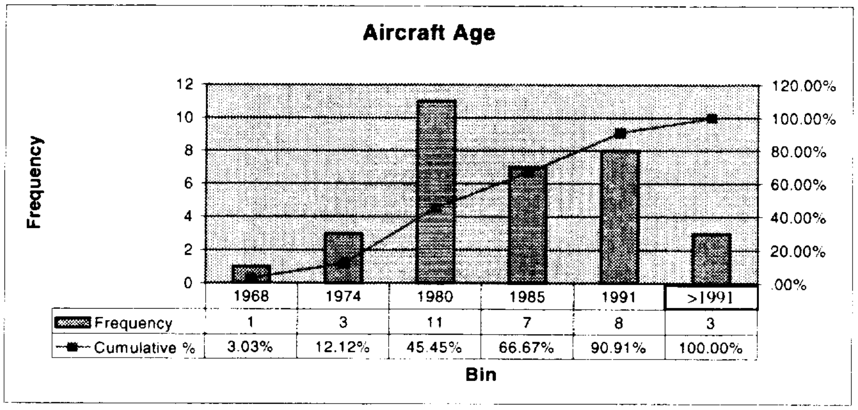


FIGURE 10: AIRCRAFT AGE DISTRIBUTION

The mean aircraft age was determined to be 18 years with a standard deviation of 7.9 years. From the random sampling of aircraft, the tables provided above indicate that the sample was comprised of a relatively good mixture of aircraft manufacturer, aircraft type, and aircraft age.

C. Failure Distribution Identification

As stated previously, of these thirty-three aircraft, twenty-three were complex and ten were non-complex. The non-complex aircraft were used in determining the reliability of the systems as defined in Section V.A. This was based on the fact that there are minimal differences between most systems of complex and a non-complex aircraft.

1. Descriptive Statistics

As stated in SAE ARP 4761, *Aerospace Recommended Practice*, probability calculations for civil aircraft certifications (not GA aircraft) are based on average probabilities and calculated for all the aircraft of the same type[3]. The failure rates are assumed to be constant over time and are estimates of mature failure rates after infant mortality and prior to wear-out. This distribution of failures is known as the exponential distribution. However, if wear-out or infant mortality is a consideration, then other methods need to be employed in order to identify the proper distribution that describes the failure process for the data. As stated previously, this report covers what was termed Complex GA Aircraft in general, not a specific aircraft of the same type, and within the previously defined constraints found in Section IV. No initial assumptions regarding data distributions were made.

Identification of failure distributions is basically a three-step process consisting of identifying candidate distributions, estimating parameters, and performing a goodness-of-fit test. Candidate distributions can be selected from histograms, descriptive statistics, analyzing the empirical failure rate, prior knowledge of the failure process, use of properties of the theoretical distribution, or construction of probability plots. If using descriptive statistics, for example, if the failure process were exponential, one would expect the mean and the standard deviation to be approximately equal (which is the case for the exponential distribution – see Appendix B)[4]. Descriptive statistics for a set of data can be easily obtained by using a software package. Excel has a statistical analysis package that allows construction of histograms as well as determination of descriptive statistics.

Tables 2 through 5 present the Complex GA Aircraft System mean and standard deviation parameters determined using Excel to develop the descriptive statistics.

Airframe Subsystem	Mean	Standard Deviation
Electrostatic Devices	5193	1959
Empennage	4370	2499
Engine Box and Cabin Fuselage	5410	2753
Exterior Coatings	2616	1602
Seats	5989	2135
Upholstery	3753	1938
Wing	3722	2009

Table 2: Airframe System Descriptive Statistics

ACS	Mean	Standard Deviation
Directional	4102	1898
Longitudinal	4188	2465
Lateral	5170	2368
Flaps	3599	2537
Trim	2900	2683
Hydraulic	3660	2645
Landing Gear	3927	2547
Steering	3458	2822

Table 3: Aircraft Control System Descriptive Statistics

Electrical Subsystem	Mean	Standard Deviation
Lighting	4918	2526
Source and Distribution	4380	2455

Table 4: Electrical System Descriptive Statistics

Powerplant Subsystem	Mean	Standard Deviation
Engine	4227	2340
Fuel	4491	2587
Heating and Ventilation	3849	2562
Propeller	3445	2372

Table 5: Powerplant System Descriptive Statistics

It is observed from the descriptive statistics that the subsystem distributions are probably not exponential (i.e., the mean does not equal the standard deviation). Only in the trim subsystem does the mean come close to the standard deviation. The implications of not being an exponential distribution indicate that the theoretical distribution may be time dependent. That is, the failure rate is not a constant value. Early failures or wear out failures may dominate. Further analysis of the data was required in order to determine the proper distribution.

2. *Probability Plots*

Probability plots also provide a method of evaluating the fit of a set of data to a distribution. Given $F(t_i)$ is an estimate of the Cumulative Distribution Function (CDF) for each failure t, if one plots the points $(t_i, F(t_i))$, $i = 1,2,...,n$, on appropriate graph paper, a proper fit to the distribution graphs would be a straight line. This is because the vertical and/or the horizontal scales have been modified to linearize the cumulative distribution function. Since straight lines are easily identifiable, probability plots provide a better visual test of a distribution than a histogram. Once again, software packages are available, which provide construction of probability plots in addition to ranking of distribution fit (i.e., Exponential, Weibull, Normal, etc.), estimating parameters of the distribution being fitted, and determination of confidence bounds for these parameters. ReliaSoft's Weibull++ 5.0 software package is an excellent tool that provides these functions and more[5]. This software provides a least-squares fit to the data, which is generally recommended rather than manually plotting data on probability paper and then fitting a straight line by eye. Over six hundred companies utilize Weibull++ software for analysis worldwide.

Appendices C through F contain the probability plots that were developed for each of the aircraft subsystems using ReliaSoft's Weibull++ 5.0. This method was used after an initial review of the descriptive statistics for the subsystem data indicated that the best-fit distribution was not exponential (See Section V.C.1.).

Of the twenty-one subsystems analyzed, the two-parameter Weibull distribution was found to best represent the sample data. This distribution was selected based on the goodness of fit, versatility, common usage in engineering, and to reduce the complexity of the data analysis. The two-parameter Weibull distribution is a time-dependent distribution that is also one of the most useful probability distributions in reliability. It can be used to model both increasing, constant, and decreasing failure rates. Beta (β) is referred to as the shape parameter. If β is less than one, the failure rate is decreasing over time. If β is greater than one, the failure rate is increasing over time. If β is equal to one, the failure rate is constant over time. Alpha (α) is called the characteristic life. This is the value at which when $t = \alpha$, and 63.2 percent of all Weibull failures occur, regardless of the shape parameter.

A summary of the results for each of the subsystems can be found in Tables 6 through 9.

Airframe Subsystem	Distribution	Parameters (2)	
		Beta	Alpha
Electrostatic Devices	Weibull	2.53	5.89E+03
Empennage	Weibull	1.16	5.03E+03
Engine Box and Cabin Fuselage	Weibull	1.42	6.28E+03
Exterior Coatings	Weibull	1.45	2.99E+03
Seats	Weibull	2.66	6.77E+03
Upholstery	Weibull	1.79	4.29E+03
Wing	Weibull	1.79	4.25E+03

Table 6: Airframe System Probability Plot Distribution and Parameters

ACS	Distribution	Parameters (2)	
		Beta	Alpha
Directional	Weibull	1.85	4729.02
Longitudinal	Weibull	1.57	4718.22
Lateral	Weibull	2.25	5843.58
Flaps	Weibull	0.95	3956.09
Trim	Weibull	0.73	2672.1
Hydraulic	Weibull	1.14	3977.39
Landing Gear	Weibull	0.92	2895.62
Steering	Weibull	1.65	3994.78

Table 7: Aircraft Control System Probability Plot Distribution and Parameters

Electrical Subsystem	Distribution	Parameters (2)	
		Beta	Alpha
Lighting	Weibull	1.66	5.61E+03
Source and Distribution	Weibull	1.67	4.95E+03

Table 8: Electrical System Probability Plot Distribution and Parameters

Powerplant Subsystem	Distribution	Parameters (2)	
		Beta	Alpha
Engine	Weibull	1.58	4.83E+03
Fuel	Weibull	1.44	5.13E+03
Heating and Ventilation	Weibull	1.60	4.19E+03
Propeller	Weibull	1.63	3.74E+03

Table 9: Powerplant System Probability Plot Distribution and Parameters

The summary of results found in these tables presents the two-parameters for the Weibull distribution. Again, the values determined for β indicate that in only a few cases, would the exponential distribution be considered as a candidate distribution.

D. Goodness of Fit

As stated previously, when using probability plotting in Weibull++, the method of linear least squares is used mathematically to fit a straight line to a set of points in order to estimate the parameters. A measure of how well a linear model fits the data is found by using the correlation coefficient, which is denoted by ρ. It is a measure of the correlation (linear relation) between the median ranks and the data. Median ranks are values used to estimate the CDF for each failure $F(t_i)$, (e.g., such as Benards approximation $MR = (j-0.3)/(N+0.4)$ where j is the rank failure position and N is the total number of failures observed). The correlation coefficient is calculated using:

$$\rho = \sigma_{xy} / (\sigma_x \sigma_y)$$

where:

σ_{xy} is the covariance of x and y, σ_x is the standard deviation of x and, σ_y is the standard deviation of y.

The range of ρ is $-1 \leq \rho \leq +1$ and the closer the value is to ±1, the better the linear fit (i.e., the paired values (x_i,y_i) lie on a straight line). A value of +1, is a perfict fit with positive slope while −1, is a perfect fit with negative slope. Table 10 below presents the goodness of fit for each subsystem using the two-parameter Weibull distribution.

Subsystem	ρ
Flap	0.99
Lateral	0.97
Longitudinal	0.98
Trim	0.98
Hydraulic	0.98
Steering	0.94
Landing Gear	0.99
Lighting	0.98
Source & Distribution	0.99
Engine	0.99
Fuel	0.95
Heating & Ventilation	0.96
Propeller	0.98
Electrostatic Devices	0.97
Empennage	0.94
Engine Box & Cabin Fuselage	0.96
Exterior Coatings	0.98
Seats	0.98
Upholstery	0.96
Wing	0.98

Table 10: Subsystem Correlation Coefficients

E. BIAS

Unbiasedness is a desirable property in point estimation where one chooses one test statistic and attempts to arrive at a reasonably close estimate to a parameter they are trying to estimate. A statistic $\hat{\theta}$ is said to be an unbiased estimate, or the value of an unbiased estimator, if and only if the mean of the sampling distribution of the estimator equals θ. Thus a test statistic is unbiased if "on the average" its values will equal the parameter it is supposed to estimate. As the sample size increases, an estimate becomes more precise.

As in most studies, until a sample was obtained and estimates were made, the parameters that describe the population were unknown. This study used a sample to estimate the parameters of a population. In order to provide a point estimate and a statement of how reasonably close the estimate was to the population parameters, the maximum error of the estimate is utilized. This concept is defined further in Section V.G.

1. Tests of Comparison

Tests of comparison are performed in order to determine whether there is significant difference between two different sets of data. Given that the samples of data may be from possibly different populations, one might wish to determine any statistically significant difference between the populations. Many methods are available in statistical literature for performing this type of test. Weibull++ allows you to compare two data sets using Reliasoft's Comparison Test with the additional capability of comparing data sets that belong to different distributions. The methodology utilized is to estimate the probability, $P[t_{2j} \geq t_{1j}]$, where decisions on whether the first population is better or worse than the second is based on the whether the probability is smaller or greater than 0.5. Here t_{2j} represents the second data sample failure set and t_{1j} represents the first data sample failure set. The estimate of $P[t_{2j} \geq t_{1j}]$, is made solving the following integral:

$$P\left[\widehat{t_{2j} \geq t_{1j}}\right] = \int_0^\infty \hat{f}_1(t) \bullet \hat{R}_2(t)dt$$

Where $\hat{f}_1(t)$ = pdf of the first data sample failure set (i.e., t_{1j}), and $\hat{R}_2(t)$ = 1-cdf of the second data sample failure set (t_{2j}).

To solve the integral, the application uses a numerical integration technique (i.e., specialized Gauss-Legendre quadrature method)[4]. Quadrature Method is a numerical method that approximates the area of a region with a curved boundary. Gauss-Legendre quadrature uses a function as a parameter to calculate an integral.

This test provides a method of answering the fundamental question, "How significant is the failure difference between products sampled from two different locations or environments?" What the test does not tell you is why are these products behaving differently in two locations. This would require additional analysis to determine these causes. Of certain interest are any gross differences between samples. The results of this test really imply the following, "Do products being used at two different locations, or in two different environments experience the same failure causes?" The test does not tell you that one sample is a better sample of the population than another sample. A sample is a point estimate. Each sample will vary from another (i.e., it is unlikely that two random samples from a population will have the same identifying parameters). Using this defined test, significant bias (i.e., each data set probably represents a different population) occurs when the probability is greater than 80 percent or less than 20 percent. If this were to occur, further analysis would be required.

Data is Biased if:	**Data is Not Biased if:**
Probability <20% and >80%	Probability >20% and <80%

Table 11: Bias Test

In general, if $P[t_{2j} \geq t_{1j}] = 0.50$ then the statement is equivalent to saying that both data sets are exactly equal (i.e., the data are from the same population), where t_{1j} and t_{2j} represent the test data from two sample populations.

If $P[t_{2j} \geq t_{1j}] < 0.50$, or specifically, if $P[t_{2j} \geq t_{1j}] = 0.10$, then the statement is equivalent to saying that t_{1j} is better representation of the population than t_{2j} with a 90% probability (e.g., the two samples are not from the same population or their operational environments have a significant effect on their failure distribution).

Of course with any sample, there will be variation. The sampling of Complex GA Aircraft alone includes many types of aircraft from several aircraft manufacturers. In addition, it should be kept in mind, that besides these two major differences, there are many other factors that may also influence the aircraft failure behavior. These factors are presented later in this report (See Section V.E.5.).

2. *Sample Data*

For each of the aircraft systems, the data sample collected can be divided into three distinct areas within the United States (i.e., Other, Virginia, and Florida – from this point on, designated OVF) to check bias. The entire data sample collected was combined into a sample population that was designated OVF. In addition, the data sample can be divided between personal owned aircraft versus aircraft located and maintained at flight schools (See Section V.E.4.). Tests of comparison were performed to determine the significant difference between samples obtained from these defined areas and to detect any significant differences between personally owned versus the aircraft sample data obtained from flight schools.

3. Area Comparison Results

Using the tests of comparison method described in Section V.E.1., the Weibull++ software generated the following subsystem area comparison results:

Aircraft Control System

1 The probability that OVF is better than Other is 53.17%
2 The probability that OVF is better than Virginia is 41.24%
3 The probability that OVF is better than Florida is 56.03%
4 The probability that Florida is better than Other is 46.28%
5 The probability that Virginia is better than Other is 63.49%
6 The probability that Florida is better than Virginia is 35.18%

Airframe

1 The probability that OVF is better than Other is 74.92%
2 The probability that OVF is better than Virginia is 41.07%
3 The probability that OVF is better than Florida is 55.84%
4 The probability that Florida is better than Other is 82.81%
5 The probability that Virginia is better than Other is 71.28%
6 The probability that Florida is better than Virginia is 65.60%

Electrical

1 The probability that OVF is better than Other is 66.35%
2 The probability that OVF is better than Virginia is 58.31%
3 The probability that OVF is better than Florida is 40.12%
4 The probability that Florida is better than Other is 75.14%
5 The probability that Virginia is better than Other is 57.71%
6 The probability that Florida is better than Virginia is 67.62%

Powerplant

1 The probability that OVF is better than Other is 66.76%
2 The probability that OVF is better than Virginia is 55.23%
3 The probability that OVF is better than Florida is 42.54%
4 The probability that Florida is better than Other is 73.18%
5 The probability that Virginia is better than Other is 62.75%
6 The probability that Florida is better than Virginia is 62.81%

These results are summarized in Table 12. For simplicity, the various levels of shading relate to the level of bias. The lightest region represents no bias. The next region of shade represents slight bias. This process is repeated for the other shaded regions.

Percent (%)	Aircraft System	Significance Comparison
35.18	ACS	FL>VA
40.12	Electrical	OVF=FL
41.07	Airframe	OVF=VA
41.24	ACS	OVF=VA
42.54	Powerplant	OVF=FL
46.28	ACS	Florida=Other
53.17	ACS	OVF=Other
55.23	Powerplant	OVF=VA
55.84	Airframe	OVF=FL
56.03	ACS	OVF=FL
57.71	Electrical	Virginia=Other
58.31	Electrical	OVF=VA
62.75	Powerplant	VA>Other
62.81	Powerplant	FL>VA
63.49	ACS	VA>Other
65.6	Airframe	FL>VA
66.35	Electrical	OVF>Other
66.76	Powerplant	OVF>Other
67.62	Electrical	FL>VA
71.28	Airframe	VA>Other
73.18	Powerplant	FL>Other
74.92	Airframe	OVF>Other
75.14	Electrical	FL>Other
82.81	Airframe	FL>Other

Table 12: Sample Differences

As depicted in Table 12, the majority of the comparisons indicate relatively little bias from the combined sample. That is, there are slight differences between aircraft used in different locations. That is, all but one of the tests of comparison indicate that the data is closely centered near the test value, 0.5, rather than the outer edges (i.e., <20% or >80%) as in accordance with Table 11. Therefore, there is no evidence supporting the statement that the data collected from different areas is not representative of the Complex GA Aircraft population.

4. *Personal Aircraft versus Flight School Comparison Results*

As in Section V.E.3., comparisons between personal aircraft and flight schools can also be assessed for bias. Again, using the tests of comparison method described in Section V.E.1., the Weibull++ software generated the following subsystem comparison results:

ACS

- The probability that Personal Aircraft are better than Flight Schools is 42.90%

Airframe

- The probability that Personal Aircraft are better than Flight Schools is 21.69%

Electrical

- The probability that Personal Aircraft are better than Flight Schools is 32.18%

Powerplant

- The probability that Personal Aircraft are better than Flight Schools is 31.42%

Again, there was insufficient evidence to state that the personal aircraft data and flight school aircraft data were significantly biased (i.e., <20% or >80%). Therefore, there was no evidence supporting the statement that the data collected from these two sources is not representative of the Complex GA Aircraft population.

Each sample above represented a random sample of the Complex GA Aircraft population. As expected, each sample varies from the other. The exact cause of these differences is unknown, but may be determined with additional analysis. Each sample can be used as an estimate of the general population. However, by combining the aircraft samples, a larger sample size was obtained which generally provides a better estimate of the population parameters.

5. *Sample Variation*

Even if it were possible to ensure that every member of a population have an equal chance of being included in a sample, it does not follow that a series of samples drawn from one population and fulfilling this criterion will be identical. Each sample will show chance variations from one to another, and that variation may be slight or considerable. As stated previously, this can be caused by a number of causes. In this study, sources of variation in the sample may be contributed to any one or any combination of the following:

- *Maintenance Replacements – Based on maintenance worker training and experience as well as periods of maintenance. As an example, flight schools are required to perform 100-hour maintenance inspections on aircraft where private aircraft owners are not.*

- *Environment – Corrosive (Saltwater and Acid Rain) or Temperature (High/Low) effects.*

- *Operational Periods – High cycle rates or usage rates.*

- *Maintenance Records – Accurately report work as a failure, maintain logbooks correctly, or readability.*

- *Pilots – Training, lifestyle, strength or personal habits.*

- *Components - Variability in manufacturing or approved parts versus non-approved parts.*

F. Reliability Estimates

A two-parameter Weibull distribution has a shape parameter β and a characteristic life parameter α. Based on the results of the probability plots for a two-parameter Weibull distribution and a six-hour representative cross-country flight, the reliability of each Complex GA Aircraft subsystem was estimated using the following reliability equation:

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

The results of this calculation are shown in Tables 13 through 16.

Airframe Subsystem				**Element Reliability**
	Beta	**alpha**	**t**	**Weibull**
	β	α **(hours)**	**(time – hours)**	$e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$
Electrostatic Devices	2.53	5.89E+03	6	0.99999997
Empennage	1.16	5.03E+03	6	0.99959336
Engine Box and Cabin Fuselage	1.42	6.28E+03	6	0.99994848
Exterior Coatings	1.45	2.99E+03	6	0.99987710
Seats	2.66	6.77E+03	6	0.99999999
Upholstery	1.79	4.29E+03	6	0.99999223
Wing	1.79	4.25E+03	6	0.99999208

Table 13: Airframe System Reliability Estimates

ACS				Element Reliability
	Beta	alpha	t	Weibull
	β	α (hours)	(time – hours)	$e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$
Directional	1.85	4729.02	6	0.9999956
Longitudinal	1.57	4718.22	6	0.9999716
Lateral	2.25	5843.58	6	0.9999998
Flaps	0.95	3956.09	6	0.9979040
Trim	0.73	2672.1	6	0.9884144
Hydraulic	1.14	3977.39	6	0.9993927
LG	0.92	2895.62	6	0.9966088
Steering	1.65	3994.78	6	0.9999780

Table 14: Aircraft Control System Reliability Estimates

Electrical Subsystem				Element Reliability
	Beta	alpha	t	Weibull
	β	α (hours)	(time – hours)	$e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$
Lighting	1.66	5.61E+03	6	0.99998831
Source and Distribution	1.67	4.95E+03	6	0.99998650

Table 15: Electrical System Reliability Estimates

Powerplant Subsystem				Element Reliability
	Beta	alpha	t	Weibull
	β	α (hours)	(time – hours)	$e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$
Engine	1.58	4.83E+03	6	0.99997436
Fuel	1.44	5.13E+03	6	0.99994005
Heating and Ventilation	1.60	4.19E+03	6	0.99997182
Propeller	1.63	3.74E+03	6	0.99997219

Table 16: Powerplant System Reliability Estimates

At this time, it should be noted that an autopilot failure rate was estimated based on one failure observed on one aircraft. That means, of all the complex aircraft sampled, only one had an autopilot. In addition, this failure was repaired (i.e., entire unit was not replaced). As a conservative approach (i.e., assume one failure) an autopilot failure rate was calculated by dividing a single observed failure event by the total number of aircraft hours accumulated on that specific aircraft. This provided a conservative estimate of 2.63×10^{-4} failures per hour. The constant failure rate (i.e., exponential) distribution is used to describe failures due to completely random or chance events. The following equation represents the exponential distribution (commonly used in reliability engineering) which was used estimate the reliability for an autopilot with a constant failure rate (i.e., λ = 2.63 X 10^{-4} failures per hour):

$$R(t) = e^{-\lambda t}$$

The autopilot reliability estimate for a six-hour mission (i.e., t = 6) is shown in Table 17 below.

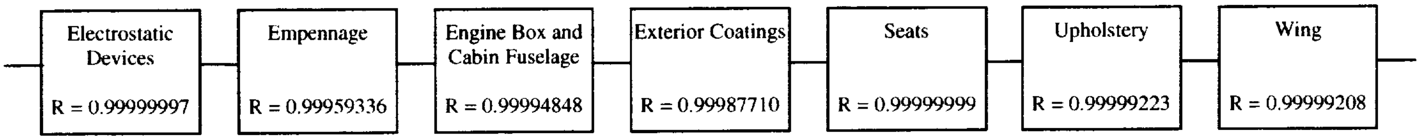
System	λ	t	Reliability
	(failures per hour)		
Autopilot	2.63 X 10^{-4}	6	0.9984232

Table 17: Autopilot Reliability Estimate

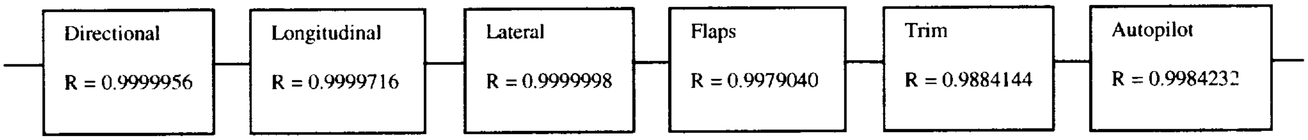
In order to assess the reliability of each Complex GA Aircraft System, series reliability block diagrams were used. The diagrams represent each system and present the concept that if a subsystem within a system fails, then the mission fails. In determining the system reliability, the following equation was used for series systems:

$$R_{System} = \prod_{i=1}^{n} R_i$$

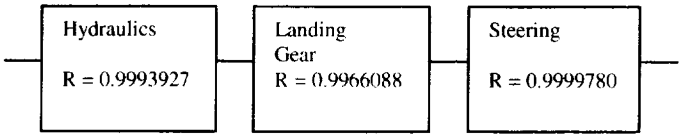
The block diagrams and associated reliabilities for each of the Complex GA Aircraft Systems are presented below:



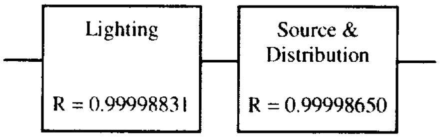
$R_{Airframe\_System} = 0.99940$



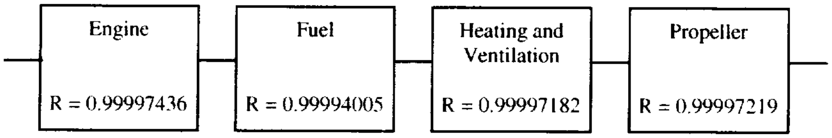
$R_{FCS\ System\ w/\ autopilot} = 0.98476$



$R_{\text{GCS System}} = 0.99598$



$R_{\text{Electrical\_System}} = 0.99997$



$R_{\text{Powerplant\_System}} = 0.99986$

G. Hazard Rates

Using the following equation, the hazard rate can be determined for a six-hour flight:

$$\lambda(t)=\left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1}$$

The results are shown in Tables 18 through 21.

Airframe				Hazard Rate
	Beta	alpha	t	λ (failures per hour)
	β	α (hours)	(time – hours)	$\left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1}$
Electrostatic Devices	2.53	5.89E+03	6	1.14E-08
Empennage	1.16	5.03E+03	6	7.86E-05
Engine Box and Cabin Fuselage	1.42	6.28E+03	6	1.22E-05
Exterior Coatings	1.45	2.99E+03	6	2.97E-05
Seats	2.66	6.77E+03	6	3.37E-09
Upholstery	1.79	4.29E+03	6	2.32E-06
Wing	1.79	4.25E+03	6	3.36E-06

Table 18: Airframe System Hazard Rate Estimates

ACS				Hazard Rate
	Beta	alpha	t	λ (failures per hour)
	β	α (hours)	(time – hours)	$\left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1}$
Directional	1.85	4728.93	6	1.35E-06
Longitudinal	1.57	4718.22	6	7.44E-06
Lateral	2.25	5843.58	6	7.08E-08
Flaps	0.95	3956.09	6	3.32E-04
Trim	0.73	2672.1	6	1.42E-03
Hydraulic	1.14	3977.39	6	1.15E-04
LG	0.92	2895.62	6	5.21E-04
Steering	1.65	3994.78	6	5.16E-04

Table 19: Aircraft Control System Hazard Rate Estimates

Electrical				Hazard Rate
	Beta	Alpha	t	λ (failures per hour)
	β	α (hours)	(time – hours)	$\left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1}$
Lighting	1.66	5.61E+03	6	3.24E-06
Source and Distribution	1.67	4.95E+03	6	3.76E-06

Table 20: Electrical System Hazard Rate Estimates

Powerplant				Hazard Rate
	Beta	alpha	t	λ (failures per hour)
	β	α (hours)	(time – hours)	$\left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1}$
Engine	1.58	4.83E+03	6	6.75E-06
Fuel	1.44	5.13E+03	6	1.44E-05
Heating and Ventilation	1.60	4.19E+03	6	7.51E-06
Propeller	1.63	3.74E+03	6	7.56E-06

Table 21: Powerplant System Hazard Rate Estimates

In order to determine the system hazard rate for failures governed by the Weibull failure law, then the following equation is utilized (See Appendix G)[5]:

$$\lambda_{System}(t) = \sum_{i=1}^{n}\left(\frac{\beta_i}{\alpha_i}\right)\left(\frac{t}{\alpha_i}\right)^{\beta_i-1}$$

Using the hazard rates presented in Tables 18 through 21, it can be seen that the system hazard rates for a 6-hour flight are:

$$\lambda_{\text{Airframe System}}(t=6) = \sum_{i=1}^{7} \lambda_i(6) = 1.25 \text{ x } 10^{-4} \text{ failures per hour}$$

$$\lambda_{\text{FCS System}}(t=6) = \sum_{i=1}^{6} \lambda_i(6) = 2.02 \text{ x } 10^{-3} \text{ failures per hour}$$

$$\lambda_{\text{GCS System}}(t=6) = \sum_{i=1}^{3} \lambda_i(6) = 6.37 \text{ x } 10^{-4} \text{ failures per hour}$$

$$\lambda_{\text{Electrical System}}(t=6) = \sum_{i=1}^{2} \lambda_i(6) = 7.00 \text{ x } 10^{-6} \text{ failures per hour}$$

$$\lambda_{\text{Powerplant System}}(t=6) = \sum_{i=1}^{4} \lambda_i(6) = 3.62 \text{ x } 10^{-5} \text{ failures per hour}$$

H. Confidence

In order to address the issue as to whether or not the results of our sample provide an estimate of the population mean that is off by at most one order of magnitude, the two following methods were used.

1. Large Sample Size

For large sample sizes (i.e., $n \geq 30$) the normal distribution was used to determine the confidence of the mean value obtained from the sample distribution. With the desired degree of precision (i.e., maximum error of estimate "E" of one order of magnitude), sample size, and sample standard deviation "s", the confidence that "s" is a good estimate of the population standard deviation "σ" can be determined using the following equation:

$$E = z_{\alpha/2} \bullet \frac{s}{\sqrt{n}}$$

2. *Small Sample Size*

For the small sample sizes (i.e., n < 30) the student t distribution was used to determine the confidence of the mean value obtained from the sample distribution. The equation is similar to that seen above:

$$E = t_{\alpha/2} \bullet \frac{s}{\sqrt{n}}$$

The difference here is that with a large sample size it is reasonable to substitute in the sample standard deviation s. With a small sample size, one must make the assumption that the sample comes from a normal population. The student t distribution has a parameter ν (i.e., degrees of freedom) that is equal to n-1.

By using the equations defined above and the mean and standard deviation estimated using descriptive statistics, confidence limits can be determined for each of the Airframe Subsystems. Typical confidence estimates are made using 0.95 and 0.99. For this study, a confidence of 0.95 is selected with corresponding $\mathbf{z}_{\alpha/2} = 1.96$. Similar values for $\mathbf{t}_{\alpha/2}$ are 1.701 (n=29) and 1.796 (n=12). It is noted here that E, stands for the maximum value of $|x - \overline{\mu}|$ (i.e. the maximum error of the estimate). This can now be added to modify the sample size equations to determine confidence bounds.

$$\mu = \overline{x} \pm \frac{(z_{\alpha/2} \bullet s)}{\sqrt{n}}$$

The results of the calculations are found in Tables 22 through 25.

	s	n	E	$-Z_{\alpha/2}$	μ	$Z_{\alpha/2}$
	Standard Deviation	**Number of Failures**	$z_{\alpha/2} \bullet \frac{s}{\sqrt{n}}$	**Lower Bound**	**Population Mean (failure time - hours)**	**Upper Bound**
Electrostatic Devices	1959	23	847	4346	5193	6040
Empennage	2499	25	1032	3338	4370	5402
Engine Box and Cabin Fuselage	2753	123	487	4924	5410	5897
Exterior Coatings	1602	14	925	1691	2616	3541
Seats	2135	105	408	5580	5989	6397
Upholstery	1938	8	1620	2133	3753	5373
Wing	2009	16	1070	2652	3722	4793

Note: Student t distribution used in calculations (i.e. small sample size, use $t_{\alpha/2}$ in place of $Z_{\alpha/2}$)

Table 22: Airframe System Error Estimates (Confidence = 95%)

	s	n	E	$-Z_{\alpha/2}$	μ	$Z_{\alpha/2}$
	Standard Deviation	**Number of Failures**	$z_{\alpha/2} \bullet \frac{s}{\sqrt{n}}$	**Lower Bound**	**Population Mean (failure time - hours)**	**Upper Bound**
Directional*	1898	29	722	3380	4102	4824
Longitudinal	2465	31	868	3320	4188	5056
Lateral	2368	35	785	4386	5170	5955
Flap	2537	45	741	2858	3599	4340
Trim	2683	49	751	2149	2900	3651
Hydraulic	2645	81	576	3084	3660	4236
LG	2547	318	280	3647	3927	4207
Steering*	2822	12	1793	1665	3458	5251

Note: Student t distribution used in calculations (i.e. small sample size, use $t_{\alpha/2}$ in place of $Z_{\alpha/2}$)

Table 23: Aircraft Control System Error Estimates (Confidence = 95%)

	S	n	E	$-Z_{\alpha/2}$	μ	$Z_{\alpha/2}$
	Standard Deviation	**Number of Failures**	$z_{\alpha/2} \bullet \frac{s}{\sqrt{n}}$	**Lower Bound**	**Population Mean (failure time - hours)**	**Upper Bound**
Lighting	2526	82	547	4731	4918	5465
Source and Distribution	2455	262	297	4083	4380	4677

Note: Student t distribution used in calculations (i.e. small sample size, use $t_{\alpha/2}$ in place of $Z_{\alpha/2}$)

Table 24: Electrical System Error Estimates (Confidence = 95%)

	S	n	E	$-Z_{\alpha/2}$	μ	$Z_{\alpha/2}$
	Standard Deviation	**Number of Failures**	$z_{\alpha/2} \bullet \frac{s}{\sqrt{n}}$	**Lower Bound**	**Population Mean (failure time - hours)**	**Upper Bound**
Engine	2340	864	156	4071	4227	4383
Fuel	2587	143	424	4066	4491	4915
Heating and Ventilation	2562	32	888	2961	3849	4737
Propeller	2372	99	467	2978	3445	3913

Note: Student t distribution used in calculations (i.e. small sample size, use $t_{\alpha/2}$ in place of $Z_{\alpha/2}$)

Table 25: Powerplant System Error Estimates (Confidence = 95%)

Accordingly, one can now say with 95% confidence that the error of the estimate of the mean values found in Tables 22 through 25, is at most "E," which is also found in the respective tables.

In order to place confidence intervals on the hazard rates, this study utilizes the Weibull parameters that were calculated with the Weibull++ software (see Appendix H). Confidence intervals for Weibull distribution parameters β and α are mathematically or computationally difficult to obtain[4]. Numerical techniques or specialized tables are usually required to calculate these values. The Weibull++ software provides a method for estimating these bounds with a desired confidence. Lower and upper bounds for each of the parameters were estimated using the properties of Maximum Likelihood Estimators. The following equations are used to estimate the upper and lower bounds[6]:

$$\text{Upper Bound } = \beta_U = \hat{\beta} \cdot e^{\left(\frac{K_\alpha \sqrt{Var(\hat{\beta})}}{\hat{\beta}}\right)}$$

$$\text{Lower Bound } = \beta_L = \frac{\hat{\beta}}{e^{\left(\frac{K_\alpha \sqrt{Var(\hat{\beta})}}{\hat{\beta}}\right)}}$$

$$\text{Upper Bound } = \alpha_U = \hat{\alpha} \cdot e^{\left(\frac{K_\alpha \sqrt{Var(\hat{\alpha})}}{\hat{\alpha}}\right)}$$

$$\text{Lower Bound } \alpha_L = \frac{\hat{\alpha}}{e^{\left(\frac{K_\alpha \sqrt{Var(\hat{\alpha})}}{\hat{\alpha}}\right)}}$$

Where K_α is defined by:

$$\alpha = \frac{1}{\sqrt{2\pi}} \int_{K_\alpha}^{\infty} e^{-\left(\frac{t}{2}\right)} dt = 1 - \Phi(K_\alpha)\pi$$

If δ is the confidence level, then α = (1-δ)/2 for the two-sided bounds, and α =1-δ for the one-sided bounds.

The variances and the covariances are estimated using the Fisher Matrix[7].

Utilizing the previous methods for estimating system hazard rates for a six-hour flight (See Section V.G.) the upper and lower bound system hazard rates were calculated. These estimates are presented in Table 26.

System	Lower System λ	System λ	Upper System λ
Electrical	3.30E-05	6.82E-06	1.26E-06
Airframe	1.96E-03	1.23E-04	4.28E-06
Powerplant	1.93E-04	3.63E-05	8.28E-06
Flight Control	5.09E-03	2.01E-03	4.13E-04
Ground Control	1.51E-03	6.37E-04	3.10E-04

Table 26: System Hazard Rate Estimates (Confidence = 95%)

In addition, lower and upper reliability bounds can be estimated by utilizing the data provided in Appendix H and the method described previously in this study (See Section V.F.) to calculate system reliability. These results are shown in Table 27.

System	Lower System Reliability Bound	System Reliability	Upper System Reliability Bound
Electrical	0.999861	0.999974	0.999996
Airframe	0.98721	0.99940	0.99998
Powerplant	0.99909	0.99986	0.99997
Flight Control	0.95055	0.98476	0.99584
Ground Control	0.98995	0.99598	0.99820

Table 27: System Reliability bounds (Confidence = 95%)

VI. Conclusion

As stated initially, the current reliability of Complex GA Aircraft Systems was unknown. The ability to gain insight into this unknown will provide the aviation community with a valuable benchmark that will assist in the development of reliability and safety requirements for future aircraft. The approach used in this study to estimate the current reliability of Complex GA Aircraft Systems (i.e., Airframe, Electrical, Powerplant, Flight Control, and Ground Control) utilized a random sample that reflects the actual aircraft-operating environment. The operational failures observed, occurred under actual operational conditions of use and environment and therefore provided valuable information, supportive to our study. The aircraft logbooks provided information on component failures as well as preventive maintenance activities (i.e., 100 hour and annual inspections). The random sampling method described within this study provided a means of estimating the reliability of Complex GA Aircraft Systems. The approach used to estimate the Cockpit Instrument reliability is described in Appendix A.

System reliability estimates are based on the probability that a Complex GA Aircraft Airframe System will successfully complete a 700 nautical mile six-hour flight. The system reliability estimates are determined to be:

System	Reliability Estimate
Airframe	0.99940
Electrical	0.99997
Powerplant	0.99986
Flight Control	0.98476
Ground Control	0.99598
Cockpit Instrumentation	0.976

Table 28: System Reliability Estimates (all calculations based on a six-hour flight)

It should be noted once again, that this study did not include aircraft that have been involved in catastrophic events caused by component failures. The ability to obtain aircraft records on such aircraft would probably require FAA involvement and also present legal issues that could not be addressed within the timeframe of this task.

The exponential distribution is not the only method that may be used to determine system failure rates. It is commonly used in reliability and provides an excellent method for estimating system reliability. The exponential method was used in the analysis of the Cockpit Instrumentation System (See Appendix A). As stated previously, probability calculations for civil aircraft certifications (not GA aircraft) are based on average probabilities that are calculated for all aircraft of the same type probabilities (i.e., failure rates are assumed to be constant). However, if wear-out or infant mortality is a consideration then other methods must be used in the determination of distribution which best fits the data. As observed in Section V.C.1., other methods were necessary and therefore employed in this reliability study to aid in the determination of the proper failure distribution that best represents the data. The data from aircraft logbooks was treated as failure data for this reliability study according to the groundrules and assumptions previously presented in Section IV. This usage was based on the fact that items were being replaced rather than undergoing preventive maintenance actions (e.g., servicing). That is, these components were determined to be no longer able to perform their designed function and were therefore replaced with a new component. Preventive maintenance actions are not performed on items that are described by an exponential distribution (i.e., constant failure rate with random failures). By identifying the proper failure distribution that describes the failure process, it was determined that an exponential distribution does not accurately represent the data and that the method of identifying theoretical distributions as described in the analysis of aircraft logbook data was therefore necessary and appropriate. The distribution that best described these failure processes was the two-parameter Weibull distribution. The Weibull distribution is widely used in engineering and can be used to model both increasing and decreasing failure rates.

The data obtained provided a random sample of Complex GA Aircraft that was sufficiently large enough to estimate the reliability of the Complex GA Aircraft Systems and provide an associated confidence that the represents the complex aircraft population, with an error of estimate that was within an order of magnitude. In addition, tests were performed to measure how well the data fit the identified distribution and to determine whether there was significant bias between data sources (See Sections V.D. and V.E.). From the goodness of fit test, the analysis results indicate that the Weibull distribution provided a very good fit of the sample data. In addition to this fit, there is a positive correlation with the sample data. In the determination of data bias within the sample, the analysis results indicate that the aircraft sample used does accurately represent data from a single population. There is no significant bias between the samples from different locations or from different sources (i.e., flight school aircraft vs. personal aircraft). Again, this indicates that the sample aircraft does represent data from a single population.

The reliability estimates presented in this report will provide the aviation community with a benchmark of the current Complex GA Aircraft System reliability, upon which future requirements and specifications can be based.

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Appendix A

CIS Report

GENERAL AVIATION AIRCRAFT COCKPIT INSTRUMENT RELIABILITY ANALYSIS

March 17, 1997

Office of Safety, Environmental and Mission Assurance

NASA Langley Research Center
Hampton, VA 23681

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Executive Summary

The Advanced General Aviation Transport Experiment (AGATE) Program is composed of a government-industry-university consortium with a goal to develop the technologies for the revitalization of the US general aviation industry. This program is designed to make the general aviation aircraft in in the US accessible to the majority of the population. This obviously requires an aircraft that is simple to operate, safe, and reliable.

To achieve the Reliability aspect of the program's goal, the baseline reliability of the instruments found in the current general aviation cockpit is needed. Those instruments provide information with which the pilot operates the aircraft. The cockpit information addressed in this report was grouped into the following six categories:

- Airspeed information.
- Altitude information.
- Attitude information.
- Advisory Panel (aircraft status) information.
- Communication information.
- Navigation information.

The data presented in this report reflects the probability that the information in the six categories listed above will be provided during a typical 700 nautical mile six-hour flight. This report also contains a summary of piloting functions, a brief description of the current cockpit information, and a fault tree designed to predict the reliability of current, typical general aviation aircraft instruments. A number of sources were used in assembling the reliability data of the current instruments. Due to proprietary concerns, those sources are not identified.

The major assumptions for this analysis are:

- Human factors were not considered.
- The aircraft used was representative of general aviation aircraft population.
- External cues and information (looking out window) were not considered.
- Criticality of information was not considered.
- All ground-based navigation aids are available.
- All components will exhibit an exponential time to failure distribution.
- Environmental elements were not considered.
- Partial failures were not considered.
- Out-of-tolerance conditions were considered failures.

With the above assumptions and available reliability information, a current general aviation aircraft would have a 0.976 probability of completing the given flight profile without loss of any of the required cockpit instrumentation information. This is the baseline against which the AGATE cockpit should be compared.

List of Acronyms

ADF	Auto Director Finder
AGATE	Advanced General Aviation Transport Experiment
ATC	Air Traffic Control
DIFTree	Dynamic Innovative Fault Tree
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
IFR	Instrument Flight Rules
ILS	Instrument Landing System
MTBF	Mean Time Between Failure
NM	Nautical Miles
VHF	Very High Frequency
VOR	VHF Omni Range

Introduction

The Advanced General Aviation Transport Experiment (AGATE) is a program being pursued by a government-industry-university consortium. The experiment has as its goal to develop new technologies that will revitalize the US general aviation industry. Future aircraft and supporting technology developed through the AGATE initiative will emphasize safety, affordability, and ease of use for a single pilot. The envisioned future aircraft system will consist of a single-engine, near-all-weather transportation aircraft and related training, airspace, and ground infrastructure systems.

This report includes considerable information from the field of aviation and the basics of flying. Readers of this report who are familiar with general aviation aircraft equipment and terminology should first review **Basic Aircraft Instruments**, beginning on page A-34.

The AGATE program is designed to make the general aviation aircraft in the US accessible to the majority of the population, as well as make personal air transportation comparable to using private automobiles for trips between 150 nautical miles (NM) and 700 NM. Such a goal requires an aircraft that is simple to operate, safe, and reliable.

In order to establish the reliability goal of a future aircraft cockpit, a baseline of the reliability of the current general aviation cockpit must first be developed. This report is an evaluation of the reliability of the current cockpit for a single-engine, Instrument Flight Rule (IFR)[1] qualified aircraft capable of transporting four people (operator and three passengers) up to 700 NM.

The purpose of this analysis is to provide the predicted reliability of the cockpit instrumentation of a typical general aviation aircraft. This prediction is based on the available empirical data obtained for this report. This data was difficult to obtain for a number of reasons – not the least of which was proprietary concerns. The major reason for the difficulty was, however, the fact that there is no central clearinghouse for the retention of such data. General aviation aircraft instruments are maintained and repaired by myriad maintenance and service facilities throughout the world.

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[1] Within the US there are several layers of airspace under control of the Federal Aviation Administration (FAA) Air Traffic Control (ATC) centers. Flight into this airspace specifically requires aircraft to be operating under IFR. IFR allows for safe operation of aircraft in weather conditions that normally prevent or reduce a pilot's ability to maintain visible reference to (1) the ground for navigation and (2) the horizon for attitude control.

An aircraft cockpit's instrumentation is designed to provide the pilot operator with various elements of information required to safely fly the aircraft. Some of that information is critical to continued safe flight; while other information is often not as critical under normal flying conditions. The criticality index of the information is highly dependent on pilot experience and training, weather conditions, and location. Since the human element was not a factor in this analysis, no judgement was made regarding the criticality index of one element over another.

Federal Aviation Regulations (FAR) Part-91 specifies the minimum instrumentation required for general aviation aircraft flying under IFR conditions. The minimum instruments are:

- Airspeed indicator.
- Altimeter.
- Magnetic Direction Indicator.
- Tachometer for each engine.
- Oil pressure gauge for each engine.
- Temperature gauge for each air-cooled engine.
- Oil temperature gauge for each air-cooled engine.
- Manifold pressure gauge for each engine if a variable pitch propeller is used.
- Fuel gauge indicating the quality of fuel in each tank.
- Two-way radio communications system and navigational equipment appropriate to the ground facilities to be used.
- Gyroscopic rate-of-turn indicator.
- Slip-skid indicator.
- Altimeter adjustable for barometric pressure.
- Clock displaying hours, minutes, and seconds.
- Generator or alternator.
- Gyroscopic pitch and bank indicator (artificial horizon).
- Gyroscopic direction indicator (directional gyro or equivalent).

This report presents the predicted reliability of the basic, FAA-required cockpit instruments. These instruments are considered typical of all IFR-capable, general aviation aircraft. There are a number of other instruments available to be mounted in general aviation aircraft, which are not required by the FAA (Loran, GPS, radar altimeter, etc.). This analysis does not consider these additional instruments.

Instrumentation is provided to the pilot via the instruments listed above. For this analysis, the cockpit reliability was the probability that these instruments would accurately provide the information for which they were designed. It was assumed that an instrument failed when it did not function normally or provide accurate information. It was assumed that the cockpit failed if the required information could not be determined by any one instrument or combination of instruments. The importance of the lost information on the total aircraft operation was not considered in this analysis. The analysis was concerned with the loss of that information and its impact on cockpit reliability. Additionally, this report disregards any information that a pilot may obtain from looking outside of the aircraft.

The information provided by the instruments was analyzed and categorized into the following six general groups:

- Airspeed information.
- Altitude information.
- Attitude information.
- Advisory Panel[2] (aircraft status) information.
- Communication information.
- Navigation information.

In order to understand how the various instruments work together to provide a synergistic knowledge environment for the pilot, one must understand the basics of piloting. The following is a brief description of the information supplied by those groups of instruments. This awareness is important in order to understanding the fault tree logic presented later in this report.

Airspeed information may be obtained by any one of three means – airspeed indicator, engine power setting, or contact with the ATC. The airspeed indication system, the primary reference for airspeed information, calculates the airspeed by measuring the difference between the total air pressure[3] and the atmospheric air pressure. The Pitot system supplies the dynamic pressure to the indicator. There is a possibility that ice may block the Pitot tube and cause the instrument to give erroneous data; so, there is a heating element in the tube that operates from electrical power supplied from the alternator. (This is a situation where weather conditions would be important if criticality was a consideration for the different events). Another way to determine airspeed is with the tachometer, which quantifies the engine power output. If the engine power is known, a pilot can deduce his airspeed. Pilots often set their cruising airspeed by engine power. A pilot may also determine airspeed by contacting and ATC center. The ATC can calculate and provide the pilot the aircraft's ground speed. The transponder enables the ATC to match its radar track with that particular aircraft. The radio is used to convey the information to the pilot.

Altitude information is normally supplied by the altimeter. The altimeter measures the difference in air pressure between the aircraft's current altitude and a reference altitude (usually sea level). It then calculates the difference in feet. If the altimeter should fail in flight, altitude information can be less-accurately calculated to complete that flight by using the vertical speed indicator and the clock on the Advisory Panel.

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[2] Advisory Panel is also known as the Annunciator Panel and the Warning/Caution Panel.

[3] Total air pressure consisting of the atmospheric pressure and the dynamic pressure caused by traveling through the air.

Assuming that the pilot knew the assigned (or observed) altitude before the altimeter failed, a simple calculation of vertical airspeed (feet per minute) over time (minutes) will provide that approximate altitude information. (While a watch may appear to be completely satisfactory replacement for the cockpit clock, it is not considered a cockpit instrument. The FAA does not make allowances for a watch to substitute for the clock).

Attitude information consists of three elements – roll, yaw, and pitch. This is important information for the pilot because he may inadvertently progress into an undesirable attitude when deprived of visual references with the ground. This is a common problem when flying at night or in conditions of limited visibility. The attitude indication system (the gyroscopic pitch, bank, and direction indicators) and Turn Coordinator are the primary instruments that provide this attitude information. They allow the pilot to determine if the wings are straight and level. The attitude indication system requires pneumatic power and the Turn Coordinator requires electrical power. Pitch information may be obtained by either direct observation of the attitude indicator or it may be deduced by observing changes in either altitude or airspeed. If an aircraft's speed is increasing, the engine power has not changed, a pilot knows that the aircraft is in a dive (pitch down). The Turn Coordinator, as its name implies, is used to make balanced turns. This is important in reducing "skid," indicating "side slip," and in improving the turn efficiency. Changes in an aircraft's yaw may be determined by the Balance Ball[4] in the Turn Coordinator or the Directional Gyro.

The **Advisory Panel** supplies information on aircraft status. The status information elements required by the FAA are fuel quantity, oil pressure/temperature, pneumatic (vacuum pressure, and ammeter[5]. Some cockpit layouts may not have all of these instruments located on the same panel. For this report, the Advisory Panel refers to the instruments, which provide the status information, not the panel, itself.

Radio **communications** are required for entering certain airspace. They are also required by the FAA for IFR flight. The transponder is part of the communications group. It identifies the aircraft to ATC.

Navigation is composed of three elements – vector navigation (sometimes refereed to as dead-reckoning), radio navigation, and pilotage. Vector navigation is used to transverse from one point to another. It uses basic mathematics, i.e., movement at a known speed, along a known bearing, for a known amount of time. Radio navigation is used for determining current position in relation to FAA navigational aids. The Auto Direction Finder (ADF) and VHF Omni Range (VOR) are used for radio navigation. These instruments use a ground-based transmitter at a known position in order to determine bearing.

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[4] The Turn Coordinator is composed of the Balance Ball and Turn Needle. For this analysis they are treated as one unit.

[5] The FAA requires a generator, not an ammeter, however its use is so universal, it is considered as a requirement for the aircraft instrumentation.

Airspeed and Attitude information are needed to maintain an aircraft's lift and control. Altitude information is very important to safe flying, especially in conditions of limited visibility. The Advisory Panel information alerts the pilot to the condition of the aircraft with information on engine status and fuel available. Communications information helps alert the pilot to flying conditions and other air traffic. Navigation information gets the aircraft to its destination and helps to avoid obstacles en route. The information for each of these groups is obtained from individual instruments or by combining information from several instruments; and there is considerable interdependence among the groups.

This analysis also includes some components and subsystems that are not physically in the cockpit; but they are important in that they supply data or power. Among these supporting subsystems are the Pitot tube system and electrical power supply. Current general aviation aircraft have two types of power to operate the instruments – electrical and pneumatic. Typical general aviation aircraft power all of their instruments by electrical power, except for the directional gyro and attitude indicator, which are powered by vacuum pumps.

Only one source of electrical power was considered – the alternator. If the alternator failed during flight, the aircraft would terminate its flight as soon as possible, even though all of the instruments may be able to function for a limited amount of time from power supplied by the battery. Electrical power is required by most instruments in the cockpit.

There are currently scores of different types of general aviation aircraft in service. Additionally, there are numerous configurations of cockpit instruments with which individual owners may customize their aircraft. The only commonality is the FAA's requirement for specific instruments. This situation results in numerous instrument configurations. As such, a reliability analysis of specific configurations is impossible. The instruments used in this analysis are typical, however, of most general aviation aircraft.

Data for this analysis was surprisingly sparse. Information on aircraft cockpit components was gathered from general aviation aircraft manufacturers and from general aviation maintenance personnel. The manufacturers tended to husband their data to its proprietary nature. Additionally, the aviation repair community (composed of thousands of small organizations) lacks the resources to collect Mean Time Between Failure (MTBF) data. (There is no FAA requirement for then to maintain such data). Data was also obtained from a commercial delivery company that operates single-engine, cargo aircraft. In addition to being similar to the aircraft under study, their aircraft had instruments and design characteristics common to all small aircraft.

This analysis did not consider mission phases. A simple mission profile of start-up to shut-down was used. Normal operating procedures call for power to all instruments throughout the flight, even though they may be used only during short phases of the flight, such as landings. The mission used in this analysis was a 700-NM trip[6]. With a mean velocity of 120 knots[7], the flight would last approximately 5.83 hours. Taking into consideration pre-and post-flight taxing, a mission time of six-hours was used. This profile is representative of a typical cross country flight.

As single model of general aviation aircraft was used for a standard configuration. Where multiple sources of aircraft instrument reliability data was available; a non-weighted[8] average was used to obtain a single MTBF number.

A number of assumptions were made in order to confine this analysis to a manageable level. Some of them were:

- Human factors were not considered.
- The aircraft used was representative of general aviation aircraft population.
- External cues and information (looking out window) were not considered.
- Criticality of information was not considered.
- All ground-based navigation aids are available.
- All components will exhibit an exponential time to failure distribution.
- Environmental elements were not considered.
- Partial failures were not considered.
- Out-of-tolerance conditions were considered failures.

The assumption concerning exponential time-to-failure distribution is critical. Although this distribution is commonly used for electronic components, its application for mechanical systems could result in questionable findings. With more detailed failure data for mechanical systems, a simulation would provide improved accuracy of predicted reliability.

This analysis utilized the fault tree methodology to predict the reliability of the current general aviation cockpit's instrumentation. Fault tree analyses have gained wide acceptance and appreciation as one of the more powerful analytic tools for the study of complex systems. They enable deductive analysis to determine possible causes of an event or action; and, they provide qualitative as well as quantitative, results. A fault tree is a graphic model of the pathways within a system that can lead to a foreseeable, undesirable event. The events are not component parts of the system being analyzed; rather, they are symbols representing the logic of analysis.

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[6] This is the maximum range AGATE requirement being considered.

[7] This is a typical cruising speed.

[8] Each MTBF number was considered as equally representative of the component's reliability.

There are three types of events used in the analysis of a cockpit instrumentation reliability fault tree:

Basic Event	The initiating fault not developed further. In this analysis a basic event is the failure of a hardware item.
Intermediate Event	The system state produced by the preceding events.
Top Event	The foreseeable undesirable event to which all fault tree logic flows.

Figure A1, Cockpit Instrumentation Reliability Fault Tree (located at the end of this section) shows the fault tree used to determine the cockpit reliability. The elements in the tree are read left to right. Its Top Event is "Loss of Cockpit Instrumentation Information." This fault tree was developed using one particular model of general aviation aircraft as a model for the basic equipment, design, and cockpit layout. To distinguish it from a second fault tree to be discussed later, this fault tree will be referred to as the "primary" fault tree.

At the second level of the fault tree, there are six intermediate events feeding into the top event. The loss of any of those intermediate events will cause the loss of the cockpit instrumentation information. The events on the second level are:

1. Loss of Airspeed Information.
2. Loss of Attitude Information.
3. Loss of Advisory Panel Information.
4. Loss of Altitude Information.
5. Loss of Navigation Information.
6. Loss of Communication Information.

Loss of Airspeed Information requires <u>all</u> of the three intermediate and basic events to occur.

> **Loss of Airspeed Indicator System**: This event requires <u>any</u> or <u>all</u> of the intermediate or basic events to occur. This include failure of the:
> Air Speed Indicator fails, and/or
> Loss of Pitot Static System.

Tachometer Fails This is a basic event.

Loss of Communications Information: This event requires any or all of the intermediate events to occur. This include failure of the:
Transponder System, and/or
Loss of Voice Communications.

Loss of Attitude Information requires any or all of the three intermediate events to occur.

Loss of Roll Information: This event requires both of the intermediate events to occur. This includes:
Loss of Attitude Indication System, and
Loss of Turn Coordination Indication.

Loss of Pitch Information: This event requires all three of the intermediate events to occur. This includes:
Loss of Airspeed Information,
Loss of Attitude Indication System, and
Loss of Altitude Information.

Loss of Yaw Information: This event requires both of the intermediate events to occur. This includes:
Loss of Directional Gyro System, and
Loss of Turn Coordination System.

Loss of Advisory Panel Information requires any or all of the intermediate or basic events to occur.

Ammeter/Vacuum Pressure Gauge Fails: This is a basic event.

Oil Temperature/Pressure Gauge Fails: This is a basic event.

Loss of Clock System: This event requires any or all of the basic events to occur. This includes:
Clock Fails, and/or
Alternator Fails.

Loss of Fuel Quantity Indication: This event requires any or all of the basic events to occur. This includes:
Right Fuel Quantity Transducer Fails,
Left Fuel Quantity Transducer Fails
Fuel Quantity Indicator Fails, and/or
Alternator Fails.

Loss of Altitude Information requires any or all of the intermediate or basic events to occur. This includes:

Altimeter Fails: This is a basic event.

Loss of Vertical Speed Information: This event requires any or all of the basic events to occur. This includes:

Vertical Speed Indicator Fails: This is a basic event.

Loss of Clock System: (See previous description).

Loss of Navigation Information requires any or all of the intermediate events to occur. This includes:

Loss of Vector Navigation Information: This event requires any or all of the intermediate or basic events to occur. This includes:

Loss of Airspeed information: (See previous description).

Loss of Clock System: (See previous description).

Loss of Heading Information: This occurs if all of the following intermediate and basic events to occur:

Loss of Turn Coordination Indication,
Magnetic Compass Fails (Basic Event), and
Loss of Directional Gyro System.

Loss of Radio Navigation: This requires all of the intermediate events to occur. These intermediate events are:

Loss of VOR: This occurs if any or all of the following basic events occur:

VOR Antenna Fails,
VOR Receiver Fails,
VOR Display Fails, and/or
Alternator Fails.

Loss of ADF: This occurs if any or all of the following basic events occur:

ADF Antenna Fails,
ADF Receiver Fails,
ADF Display Fails, and/or
Alternator Fails.

Loss of Instrument Landing System (ILS): This occurs if any or all of the intermediate events occur. These intermediate events are:

Loss of Localizer/Glideslope Signal: This occurs if any or all of the following basic events occur. These intermediate events are:
ILS Receiver Fails,
ILS Localizer Antenna Fails,
ILS Glideslope Antenna Fails, and/or
Alternator Fails

Loss of ILS Display: This occurs if any or all of the following basic events occur:
ILS Display Fails, and/or
Alternator Fails.

Loss of Marker Beacon Signal: This occurs if any or all of the following basic events occur:
Marker Beacon Receiver Fails,
Marker Beacon Antenna Fails, and/or
Alternator Fails

Loss of Communications Information occurs if any or all of the following intermediate events occur.

Loss of Voice Communications: This occurs if any or all of the following basic events occur:
Communications Radio Fails,
Communications Antenna Fails, and/or
Alternator Fails

Loss of Tracking Signal: This occurs if any or all of the following basic events occur:
Transponder Fails,
Transponder Antenna Fails, and/or
Alternator Fails

From the primary fault tree, it can be seen that several basic and intermediate events occur multiple times. The alternator, which is the sole source of electrical power, is the most prominent. It is emphasized that there is only one alternator on the type of aircraft in this study.

In that fault tree, the loss of a particular component did not necessarily mean a loss of information; because, a pilot could cross check[9] his instrument panel and obtain the information with other instruments.

---

[9] Scanning of instrument panel to double-check instrument readings.

An alternative fault tree was developed in an excursion to establish the reliability of the cockpit instruments as a function of simple, straightforward hardware failures – independent of the information those same instruments would provide, as was done in the primary fault tree. In this alternative fault tree, every hardware item was a basic event to the top event, "Loss of Cockpit Instrumentation." Every hardware item fed to the Top Event as an "or" gate. There were no intermediate events. Due to its simple nature and unremarkable revelations, the alternative fault tree is not included in the report.

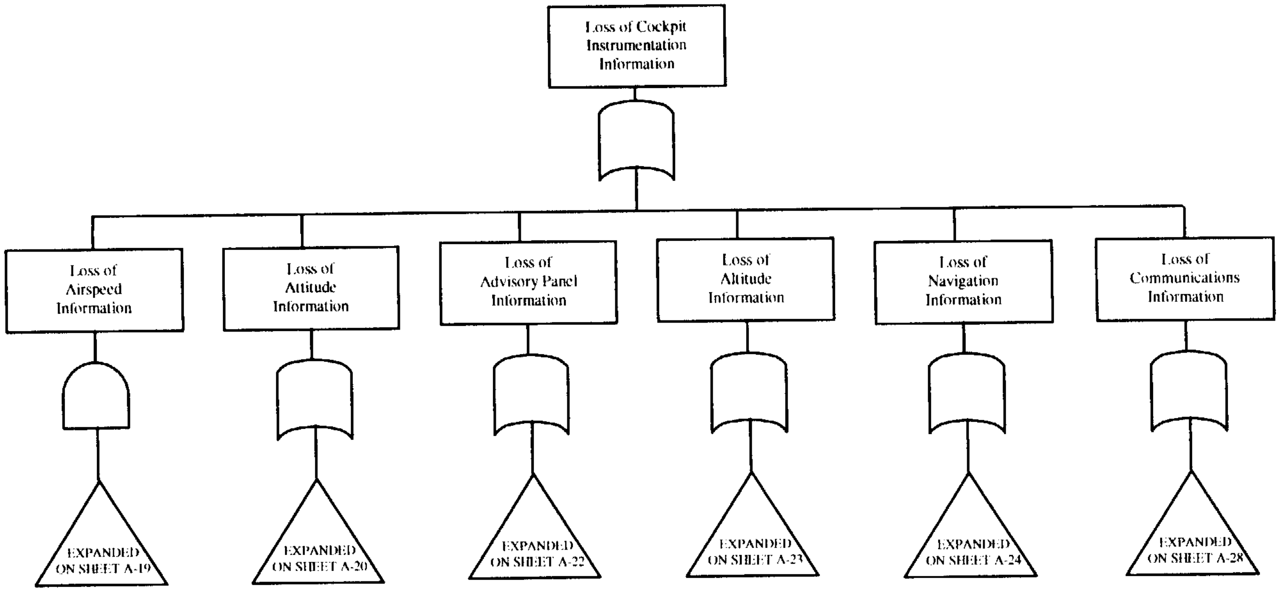


Figure A1. Cockpit Instrumentation Reliability Fault Tree

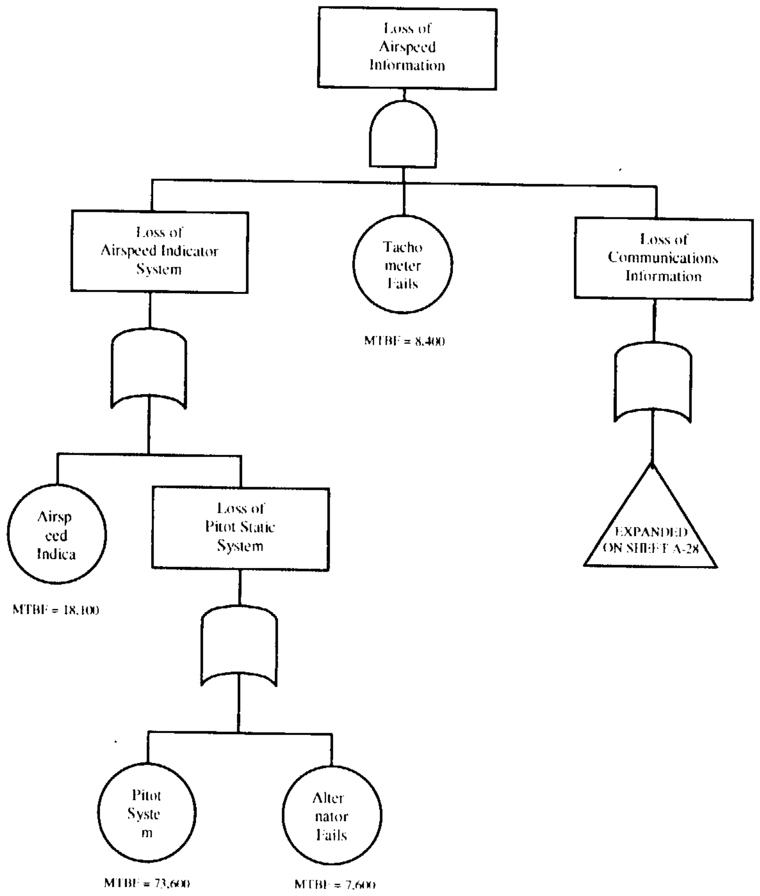


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

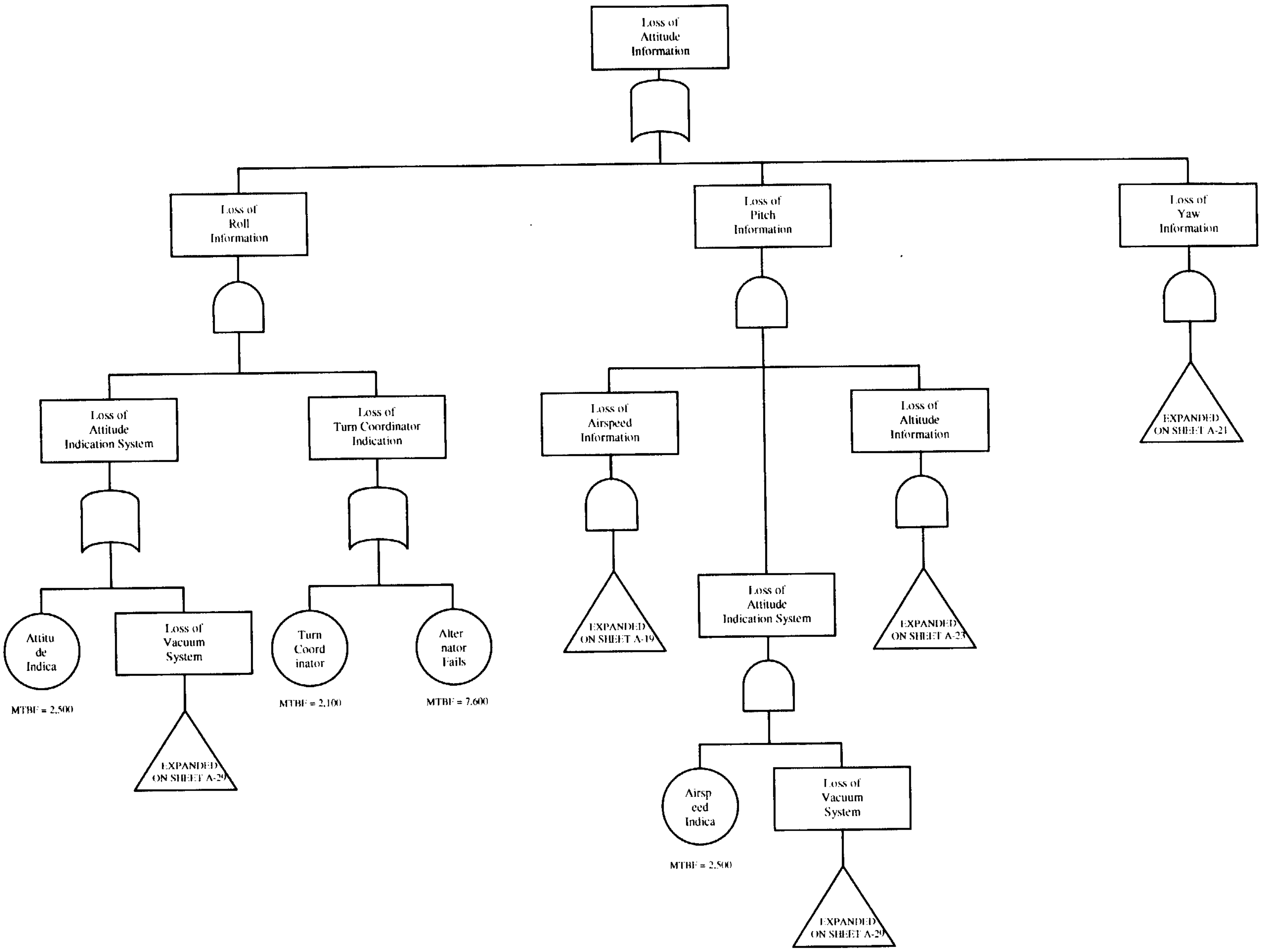


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

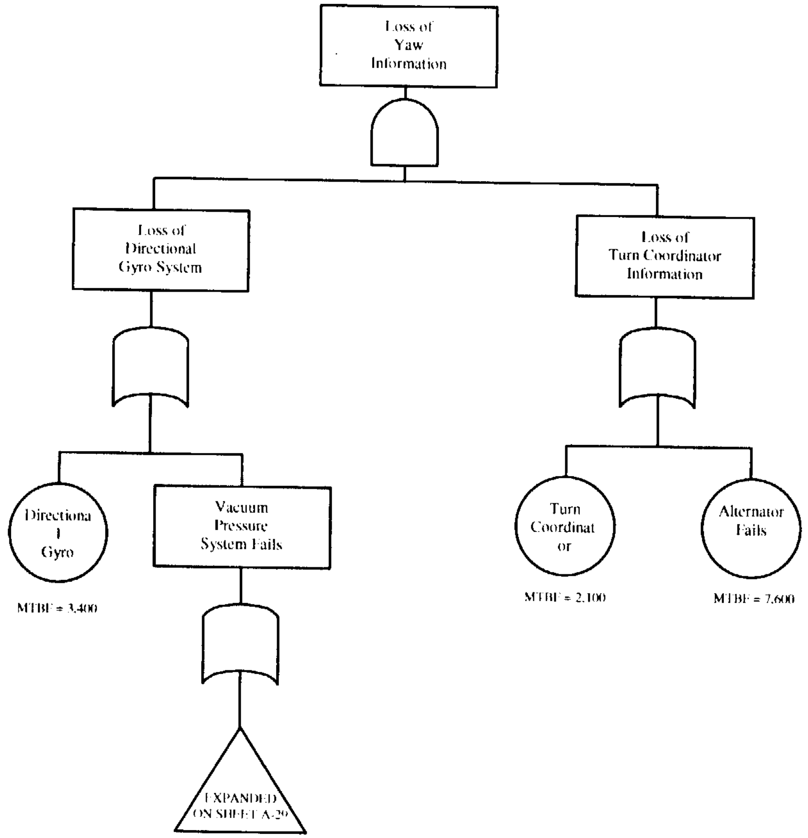


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

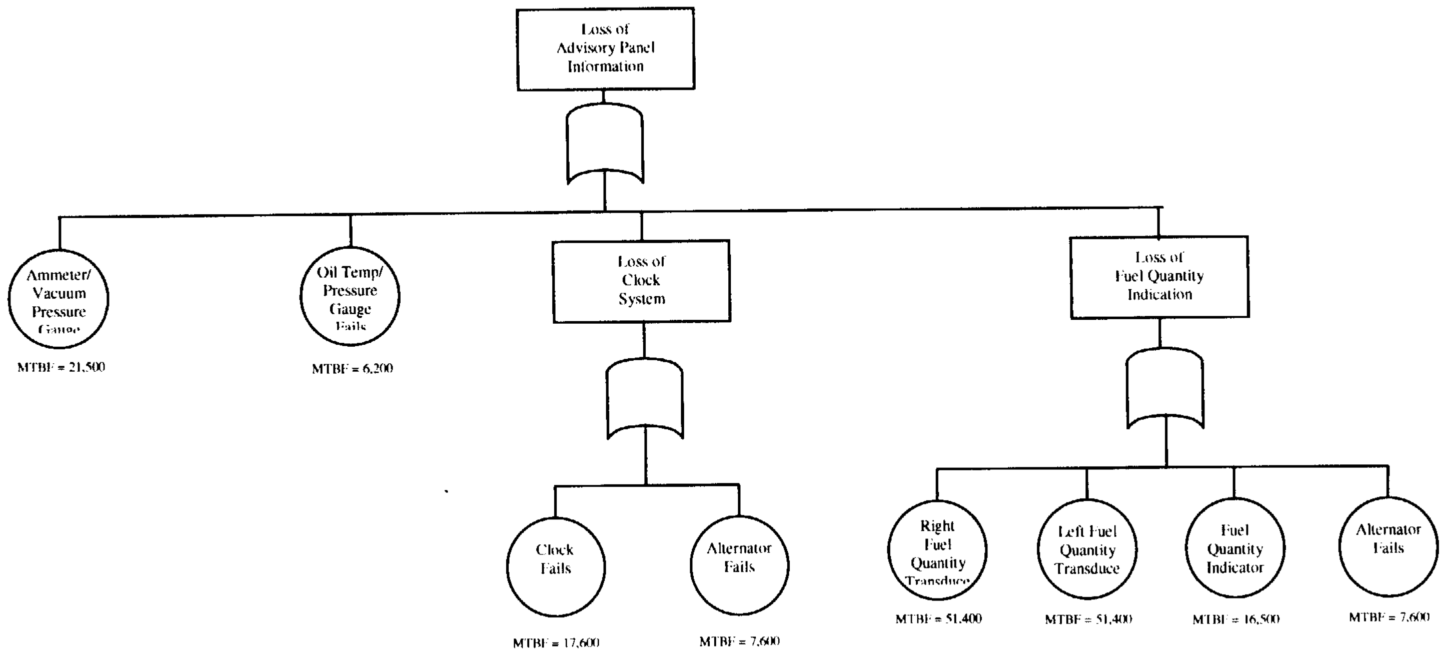


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

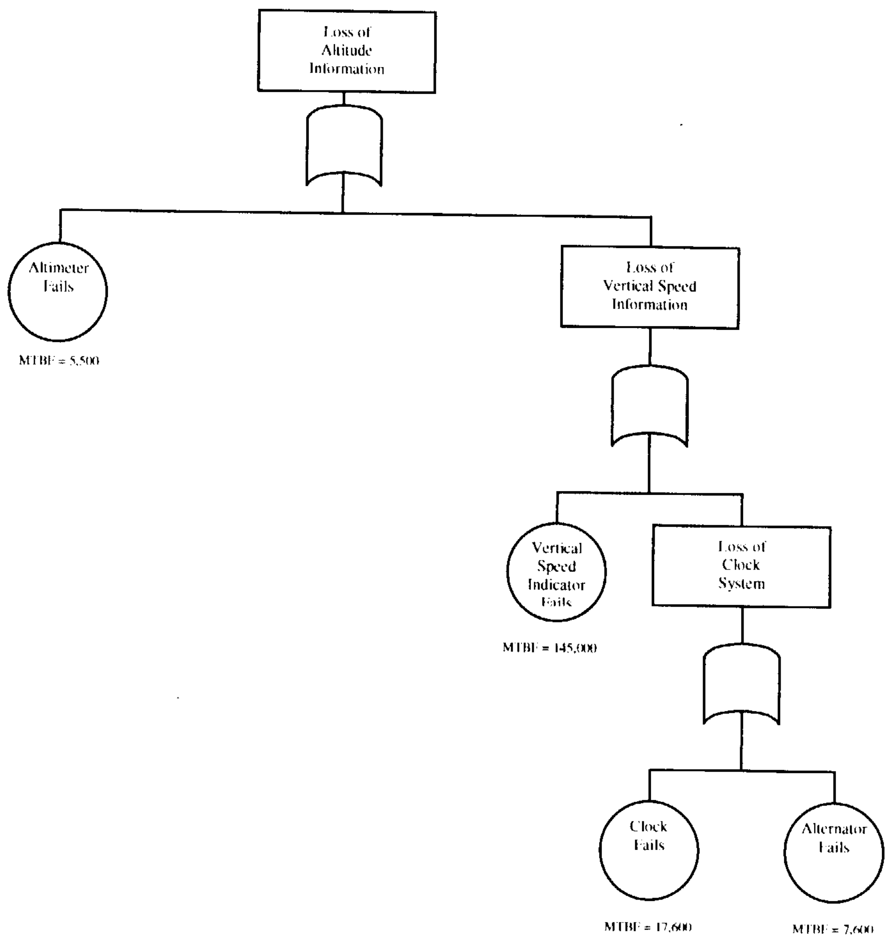


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

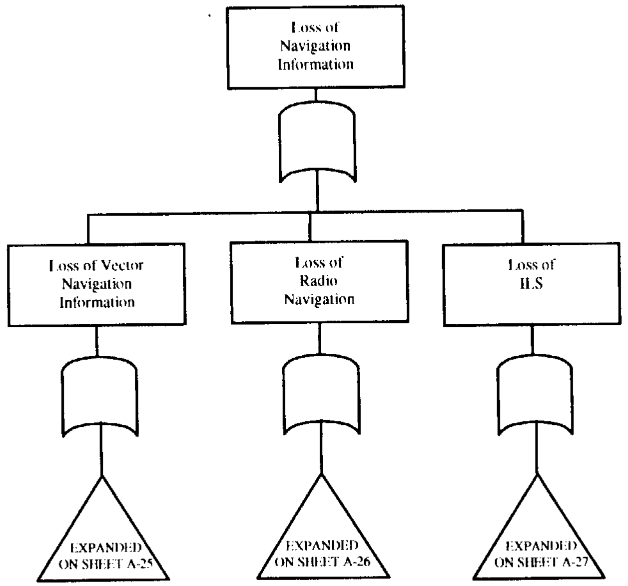


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

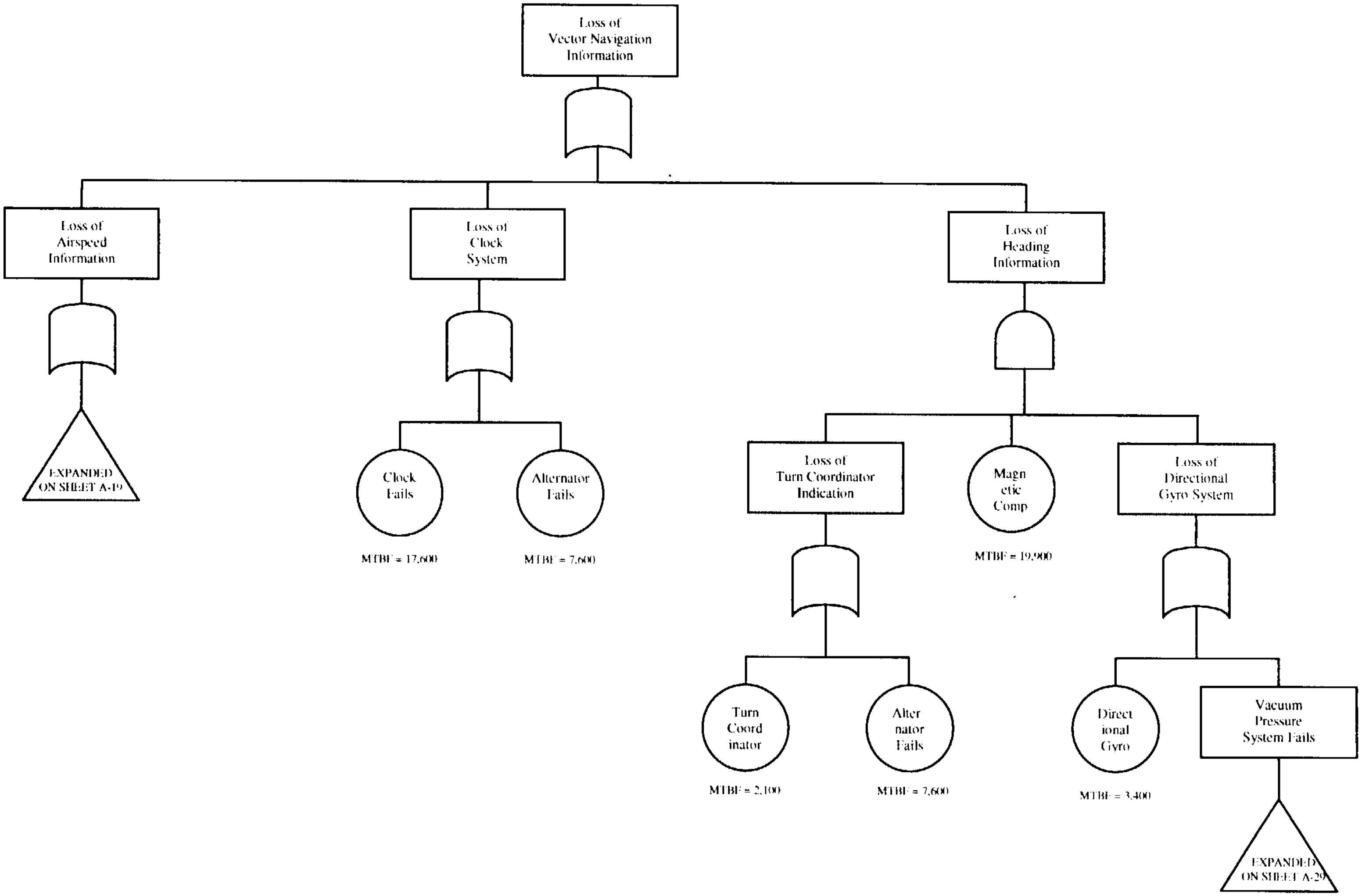


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

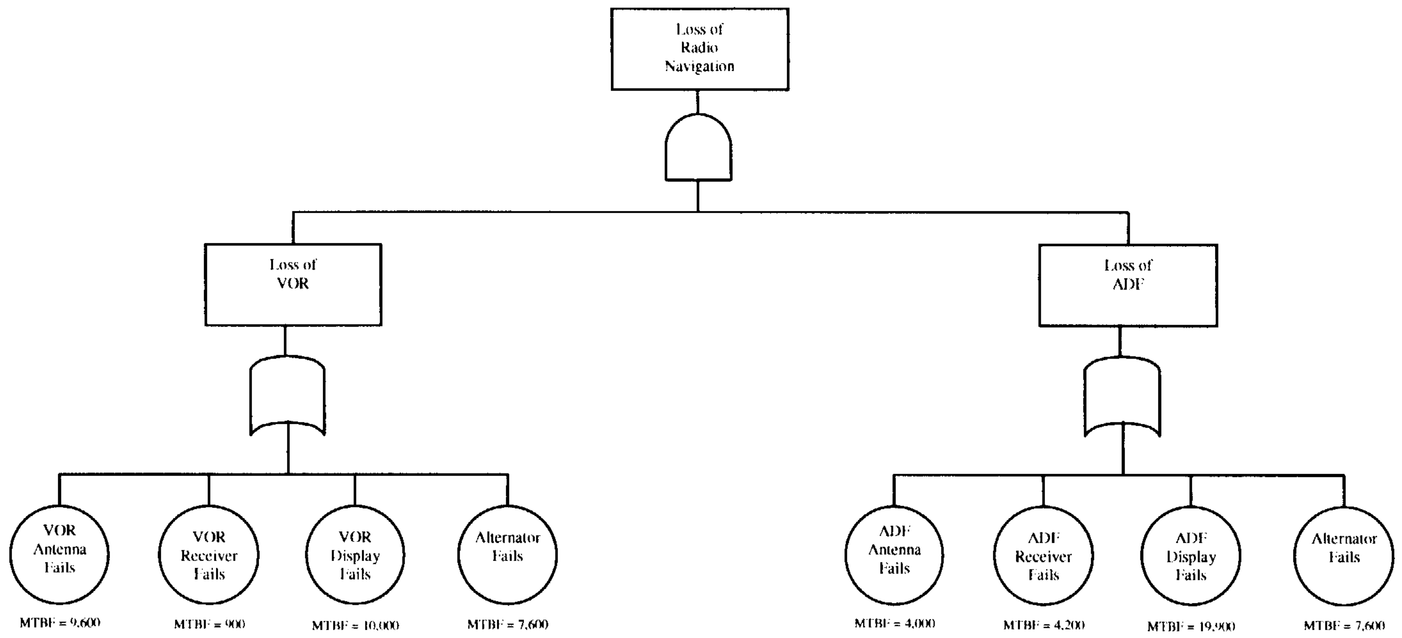


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

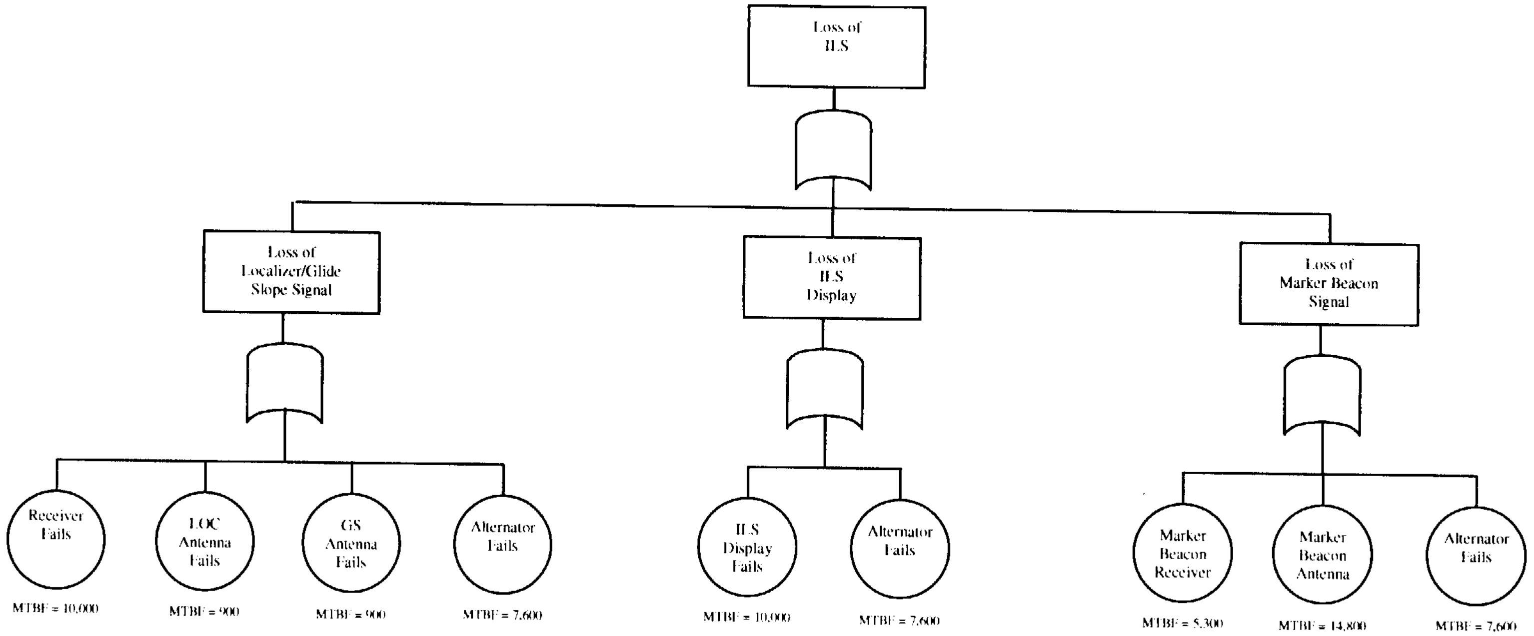


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

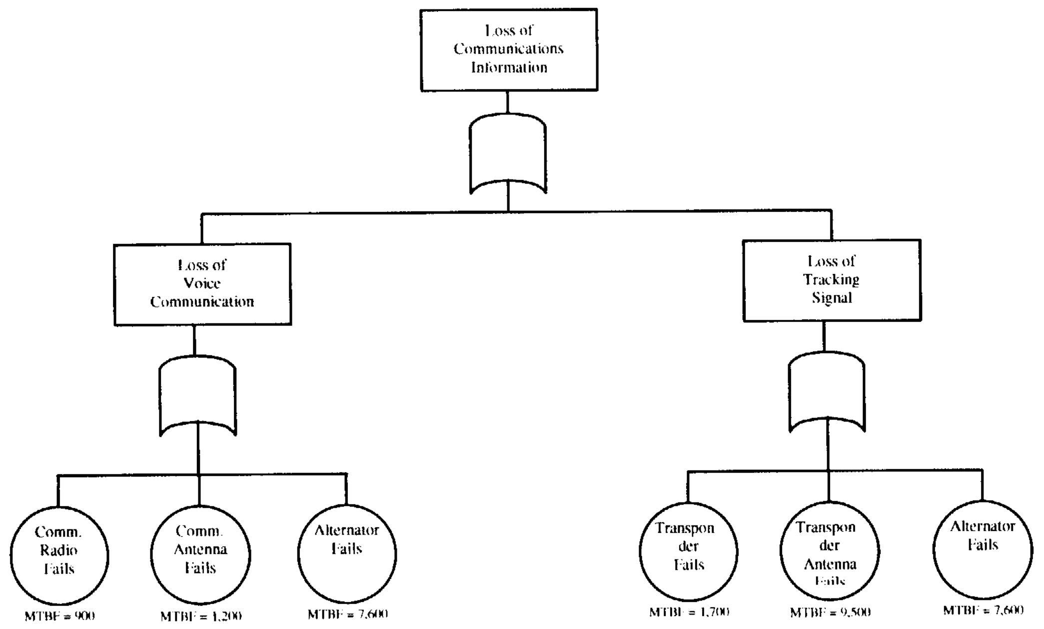


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

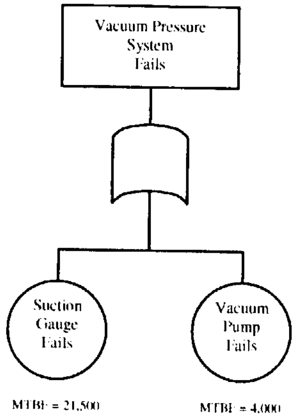


Figure A1. Cockpit Instrumentation Reliability Fault Tree (Continued)

Analysis Results

This analysis shows that the current general aviation cockpit has little redundancy in its design. Presently, flight safety and success relies heavily on pilot training and situational awareness. Today's pilots receive extensive training in cross-checking and emergency procedures. One of the goals for the aircraft envisioned in the AGATE Program is to relieve the necessity of this comprehensive training by incorporating the cross-checking processes into the instruments, thereby greatly simplifying the piloting procedures.

This analysis predicts that a current general aviation aircraft, on a 700 NM trip taking approximately six-hours, would have a 0.976 probability of completing that trip without losing any cockpit instrumentation information. The fault tree model calculated an unreliability of 0.024. Unreliability is the probability that the system will experience a failure that will result in the loss of information during its six-hour flight. This indicates that there is a 0.024 probability that the pilot will lose some cockpit instrumentation information during a six-hour flight.

This compares with a prediction of 0.041 probability that at least one instrument will fail, as calculated by the pure hardware-failure fault tree (not included). That was the situation where every component was a basic event to the "Loss of Cockpit Instrumentation Information" event. This appears to be a significant difference in unreliability. More detailed reliability data is required in order to evaluate whether this is a statistically significant difference. The use of cross-checking for information from multiple instruments appears to improve cockpit information reliability. This is what would be expected. The 0.041 unreliability may be put into these terms – there is a 0.041 probability that at least one of the instruments required will fail. There is a 0.959 probability that a six-hour mission will be completed without a component failing.

The unreliability predictions for each of the intermediate events in the primary fault tree are tabulated in **Table A1, Intermediate Event Tree Unreliability**. The unreliability for each of these intermediate events was calculated independently of each other so that common, shared intermediate and basic events were not duplicated in the calculations. The "Alternator Fails," is the most common shared basic event.

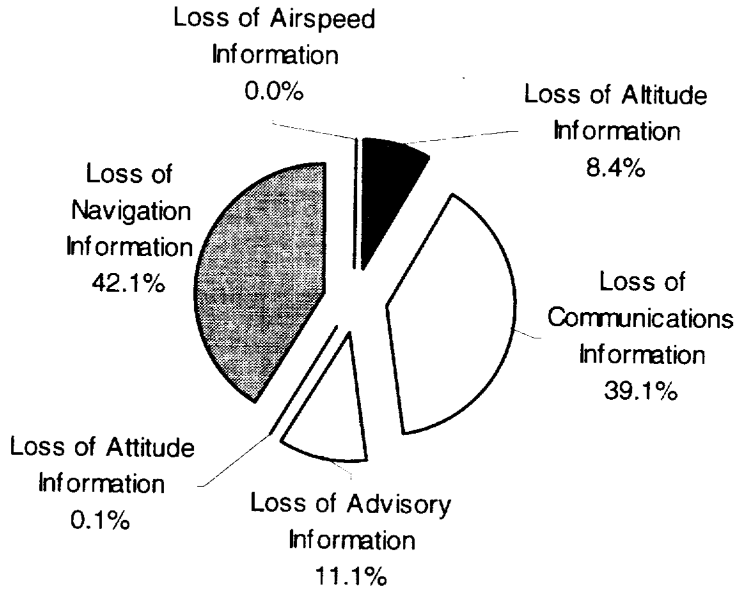
Intermediate Tree Event	Unreliability	% of Total Unreliability
Loss of Airspeed Information	5.63×10^{-7}	0.0%
Loss of Altitude Information	2.26×10^{-3}	8.4%
Loss of Advisory Information	2.97×10^{-3}	11.1%
Loss of Attitude Information	5.16×10^{-5}	0.1%
Loss of Communications Information	1.05×10^{-2}	39.1%
Loss of Navigation Information	1.11×10^{-2}	42.1%

Table A1. Intermediate Event Tree Unreliability

The percentage that each group of information contributes to the unreliability is presented in **Figure A2, Information Unreliability Percentage Breakdown**. As depicted, the loss of airspeed and attitude information contribute only a miniscule amount – while the communications and navigation information loss combine for almost 80% of the unreliability.

There are two sources for the relative large unreliability displayed by the "Loss of Communications and Navigation" information events.

Figure A2. Information Unreliability Percentage Breakdown



One cause of the relatively high unreliability is the low reliability of the components in the basic events. The reliability data is presented in **Table A2, Component Reliability Data**. Several of the components feeding into the "Loss of Communications and Navigation" intermediate events have relatively low reliability. The columns on the right side of the table indicate which "Loss of Information," intermediate event is influenced by the individual component (basic events).

The second cause of the high unreliability can be noticed from the fault tree representation. The equipment that composes the basic events in the intermediate events are all required to function in order for the event not to fail. This is the opposite of what is experienced in the "Loss of Attitude, Airspeed, and Altitude information intermediate events. In those functions, there were multiple ways to get the information. The failure of a particular component or lower intermediate event did not automatically cause the failure of the higher intermediate event. Airspeed information would have to lose three paths in order to be lost. Although the advisory Panel relied on all of its intermediate and basic events, the components involved were relatively reliable.

			Intermediate Event Influenced					
Component	**MTBF**	**λ(/hr)**	Airspeed	Altitude	Attitude	Advisory	Navigation	Communications
ADF Antenna*	4000	2.50E-04					X	
ADF Display*	19900	5.03E-05					X	
ADF Receiver*	4200	2.38E-04					X	
Airspeed Indicator	18100	5.52E-05	X		X		X	
Altimeter	5500	1.82E-04		X	X			
Alternator	7600	1.32E-04	X	X	X	X	X	X
Attitude Indicator	2500	4.00E-04			X			
Clock	17600	5.68E-05		X	X	X	X	
Directional Gyro	3400	2.94E-04			X		X	
Fuel Quantity Indicator	16500	6.06E-05				X		
Fuel Quantity Transducer*	51400	1.95E-05				X		
ILS Antenna*	900	1.11E-03					X	
ILS Display*	10000	1.00E-04					X	
ILS Receiver*	900	1.11E-03					X	
Magnetic Compass	19900	5.03E-05					X	
Marker Beacon Antenna*	14800	6.76E-05					X	
Marker Beacon Receiver*	5300	1.89E-04					X	
Oil Pressure/Temperature Gauge	6200	1.61E-04				X		
Pitot Tube*	73600	1.36E-05	X		X		X	
Radio (Comm) Antenna*	1200	8.33E-04	X		X			
Radio (Comm) Radio*	900	1.11E-03	X		X			
Vacuum Gauge*	21500	4.65E-05			X	X		
Tachometer	8400	1.19E-04	X		X		X	
Transponder*	1700	5.88E-04	X		X			X
Transponder Antenna*	9500	1.05E-04	X		X			X
Turn Coordinator	2100	4.76E-04			X		X	
Vacuum Gauge*	21500	4.65E-05			X	X		
Vacuum Pump*	4000	2.50E-04			X			
Vertical Speed Indicator	145000	6.90E-06		X	X			
VOR Antenna*	9600	1.04E-04					X	
VOR Display*	10000	1.00E-04					X	
VOR Receiver	900	1.11E-03					X	

Table A1. Intermediate Event Tree Unreliability

This analysis indicates that system which incorporate mechanical components experience very high reliability – particularly the airspeed and attitude. This runs counter to the expectations that electronic parts are more reliable than mechanical parts. There are several major factors, however, that effects this result. First, there are several crosschecks for the information. This is similar to having built-in redundancy (redundancy being the fundamental method for improving reliability in any design). Secondly, the reliability data may not accurately reflect the true reliability. The limited data available may not represent a significant sample size. Also, there may be some bias in the data. Data collected on aircraft currently in mass production (for quality control objectives) may be different from data collected from developmental projects (for design validation and verification).

Another considerable factor is that most of the mechanical instruments do not fail in a catastrophic manner. There most common failure mode is to gradually go out of specified tolerances. As the item starts to gradually fail, operators will notice this and preventive maintenance is performed before actual failure of the instrument. These tolerances are also checked during scheduled inspections. This analysis did not consider failure modes, only the basic good/failed condition.

Lastly, the assumption that mechanical parts display an exponential time to failure distribution may distort the prediction. The data collected gave no indication of their time-to-failure distribution. Without more information from the manufacturers on matters such as quality control or environmental control factors, it cannot be determined if any distortion of the data may have occurred. The exponential time-to-failure distribution assumptions are used to simplify the models to a point where an analytical solution exists.

The results of this analysis indicate that there is approximately a one-in-forty chance of losing some portion of the cockpit instrumentation information during a six-hour flight.

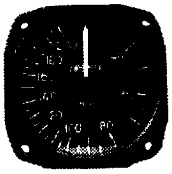
Further analysis of the cockpit reliability will require additional data. The limited availability of the data needed for this analysis suggests that a new, cohesive effort is necessary to collect instrumentation reliability data.

Basic Aircraft Instruments

There are many names used for instruments found in a general aviation cockpit. The following instruments are used throughout this report. These descriptions presented here are meant only for familiarization. There are numerous manufacturers of these instruments and their appearance may differ from one manufacturer to another: however, their basic functions are the same. Some models may combine several of these primary instruments into one unit.

Airspeed Indicator

This instrument tells the pilot the speed at which the airplane is flying through the air. This value is different from the ground speed because the air surrounding the aircraft is affected by the currents aloft.

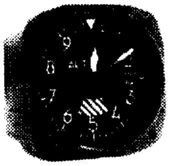


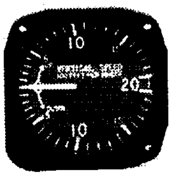
Attitude Indicator

Also called the Artificial Horizon, this gyroscopic instrument tells the pilot if the airplane is in a nose-high or a nose-low attitude; or, if the airplane is banked to the left or to the right. This is the basic instrument used to fly in the clouds.

Altimeter

The altimeter indicated at what height the airplane flies compared to sea level. It can be adjusted for changes in barometric pressure.



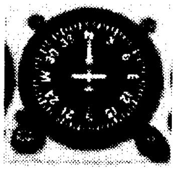


The Vertical Speed Indicator

This instrument tells the pilot if the airplane is climbing or descending, and if so, at what speed (in feet per minute).

Heading Indicator

This is a gyroscopic instrument that is used like a compass, only it is more precise and more stable during climbs, descents, and turns. It is also called a directional gyro.

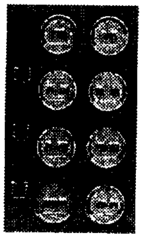


Turn Coordinator

In a turn, this instrument gives the pilot an indication of the rate of turn (how long it will take to turn 180° for example). It also includes the ball, that shows if the flight is coordinated (symmetrical) or not.

Tachometer

This instrument allows the pilot to precisely set the engine RPM.

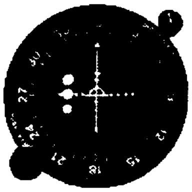


Engine Gauges

These gauges are used to monitor engine performance. They include oil temperature, oil pressure fuel quantity, engine power, and engine temperature. The fuel quantity and oil temperature are among the most important ones.

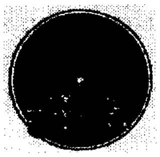
VOR

The VHF Omni Range (VOR) is a radio navigation instrument. Its Course Deviation Indicator (CDI) gives the pilot an indication on the position of the airplane in relation to a ground station. The VOR is the primary system used to define airways.



ILS

The instrument Landing System is a very sensitive VOR that also includes vertical information. It is used for precision approaches and landing in bad weather conditions.



ADF

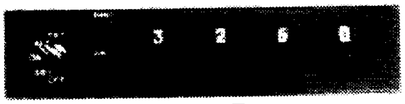
The needle of the Automatic Direction Finder always points towards the ground station on which frequency the receiver is operating (acting like an “artificial North pole”). This radio-navigation instrument is also called a radio-compass.

Radios

There are two kinds of aircraft radios – voice transceivers that are used by the pilot to talk with Air Traffic Controllers, and radio-navigation equipment which are the VOR or ADF receivers.

Transponder

Whenever it is interrogated by a RADAR, the transponder sends back a 4-digit code along with altitude information. This allows Air Traffic Controllers to identify the aircraft displayed as echoes on their RADAR screens.



Appendix B

Exponential Distribution

Properties

In reliability engineering the mean time to failure (MTTF) is defined by:

$$\text{MTTF} = E(T) = \int_0^{\infty} tf(t)dt = \int_0^{\infty} R(t)dt \qquad \text{Eq. 1}$$

which is the mean, or expected value of the probability distribution defined by $f(t)$.

Variance, or σ^2, is the average squared distance a failure time will be from the MTTF. It is a measure of spread or dispersion about the mean defined by:

$$\sigma^2 = \int_0^{\infty} (t - MTTF)^2 f(t)dt = \int_0^{\infty} t^2 f(t)dt - (MTTF)^2 \qquad \text{Eq. 2}$$

The standard deviation, σ, has the same units as the mean and is defined by:

$$\sigma = \sqrt{\sigma^2} \qquad \text{Eq. 3}$$

For the exponential distribution, reliability $R(t)$ is defined as:

$$R(t) = \exp\,[\int_0^{t} \lambda dt'] = \exp(-\lambda t) \qquad \text{Eq. 4}$$

and the probability density function is defined as:

$$f(t) = -\frac{dR(t)}{dt} = \lambda \exp(-\lambda t) \qquad \text{Eq. 5}$$

Therefore, to define MTTF for the exponential distribution using equations 1 and 4, it is found that:

$$\text{MTTF} = E(T) = \int_0^{\infty} R(t)dt = \int_0^{\infty} \exp(-\lambda t) = \left.\frac{\exp(-\lambda t)}{-\lambda}\right|_0^{\infty} = \frac{1}{\lambda} \qquad \text{Eq. 6}$$

Similarly, using equation 2, integration by parts and the results for MTTF, the variance for the exponential distribution can be determined:

$$\sigma^2 = \int_0^{\infty} t^2 f(t)dt - (MTTF)^2 = \int_0^{\infty} t^2 \exp(-\lambda t)dt - (\frac{1}{\lambda})^2 = (\frac{1}{\lambda})^2 \qquad \text{Eq. 7}$$

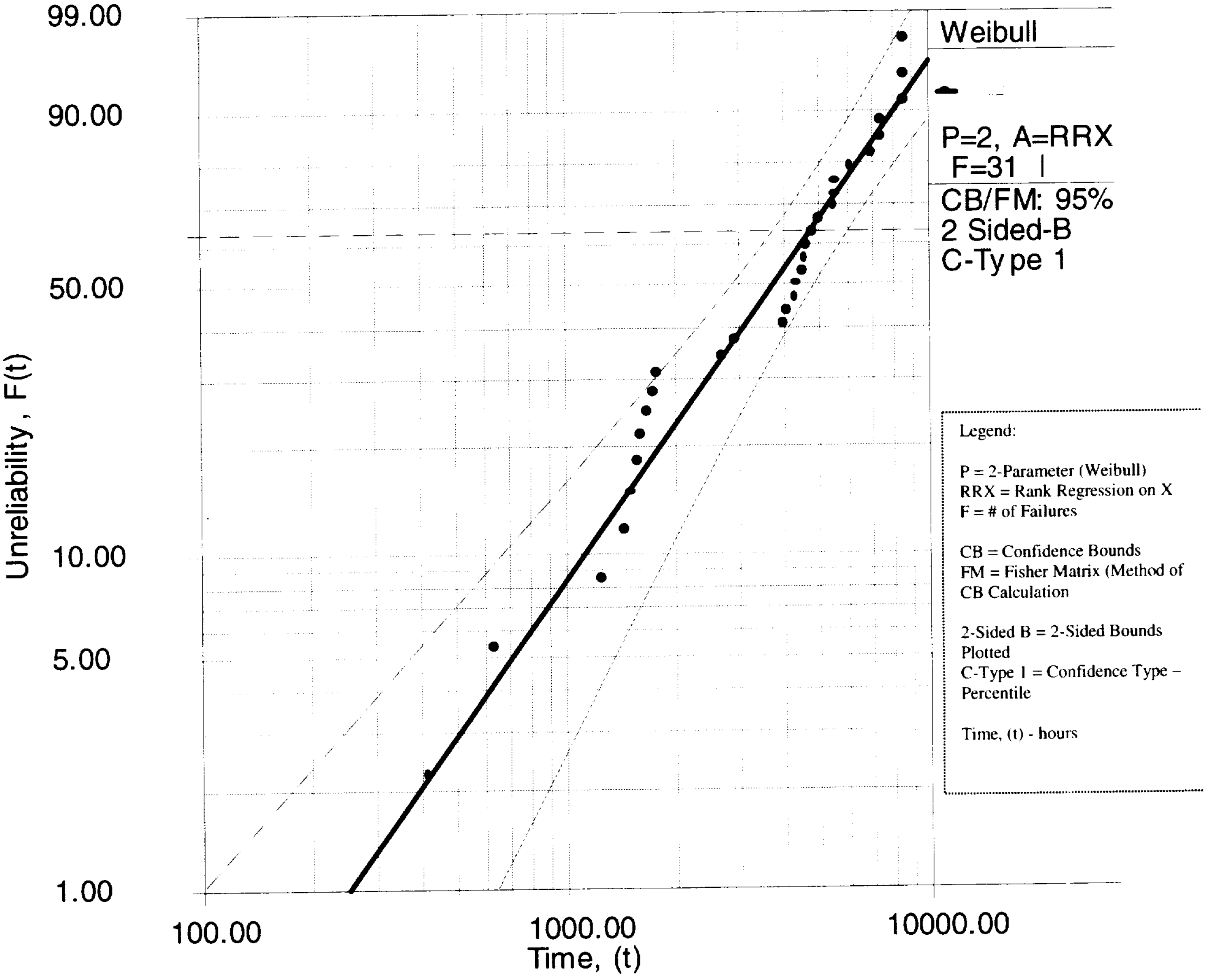
Using the results from equations 6 and 7, along with equation 3, it can now be seen that for the exponential distribution,

$$\text{MTTF} = \sigma = \frac{1}{\lambda}$$

Appendix C

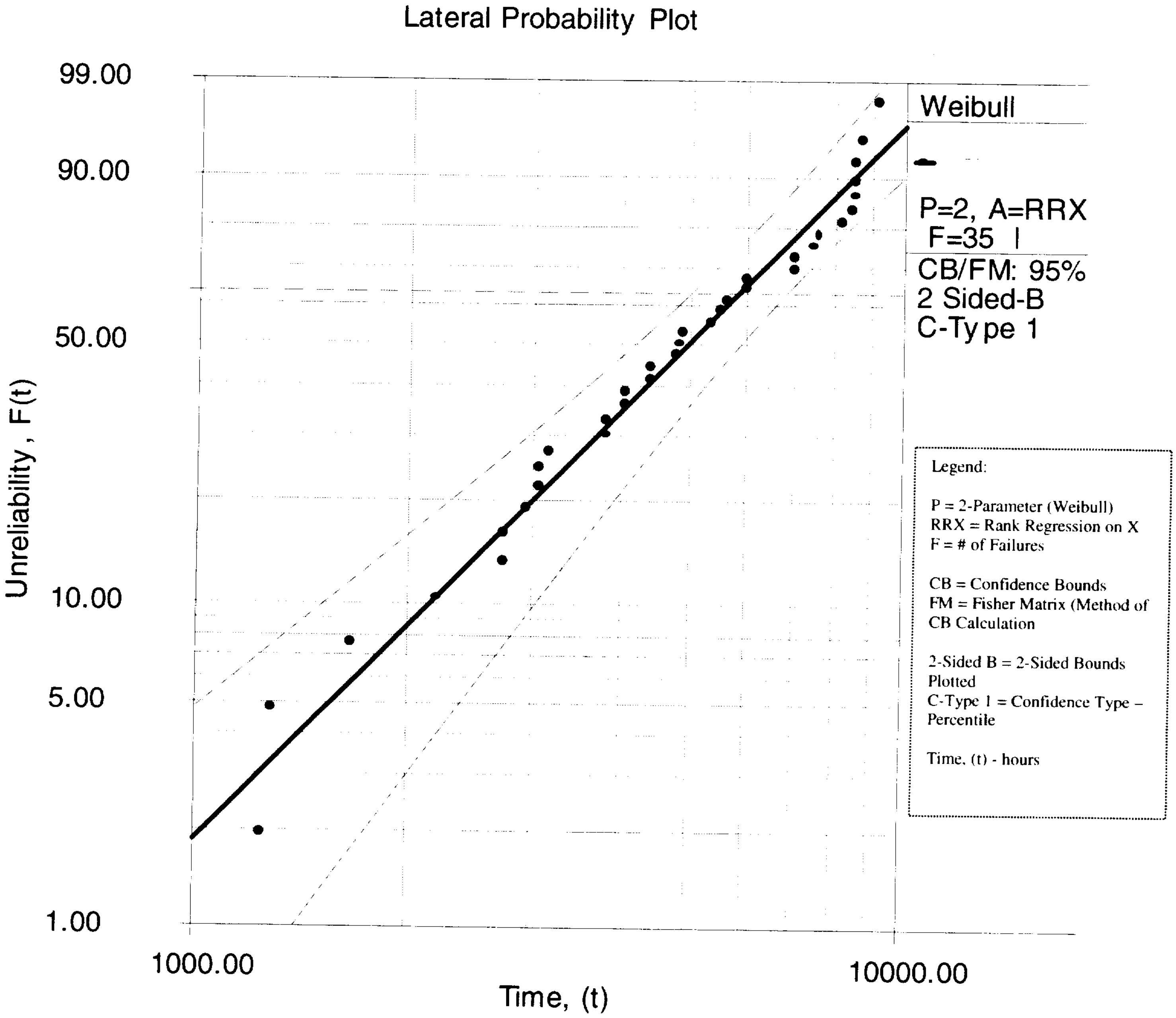
Control System

Probability Plots

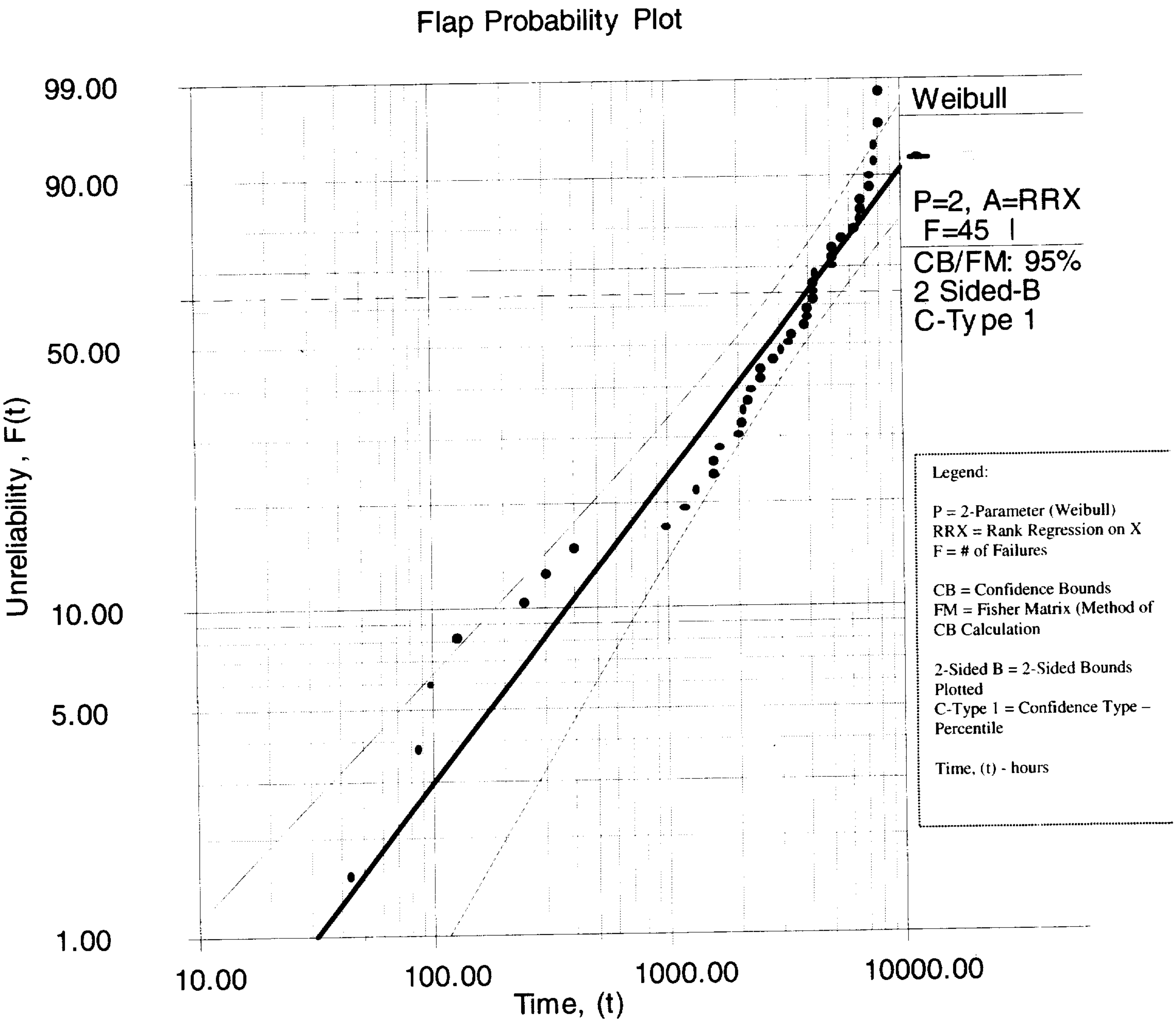


Longitudinal Probability Plot

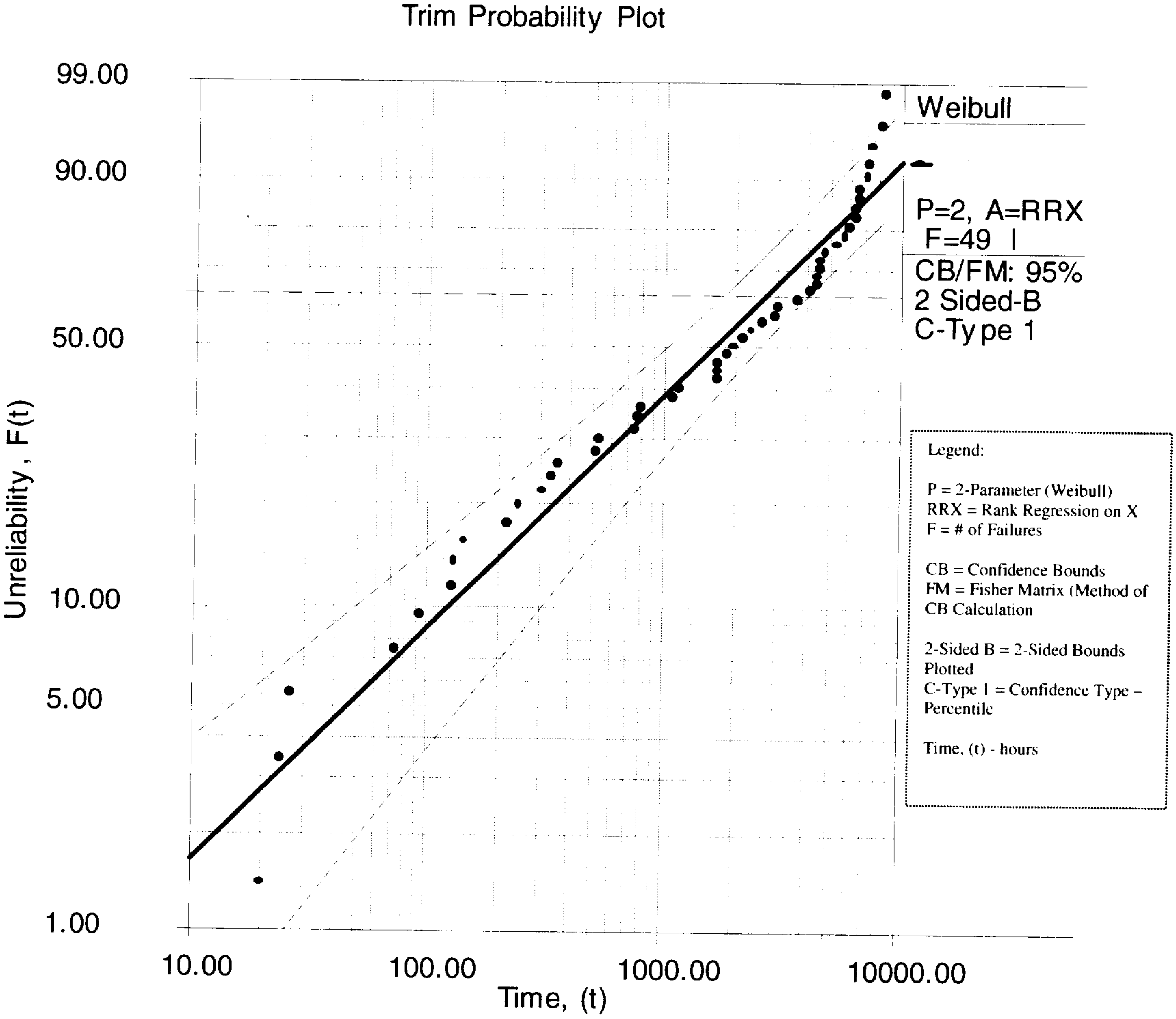
β=1.57, η=4718.22, ρ=0.98



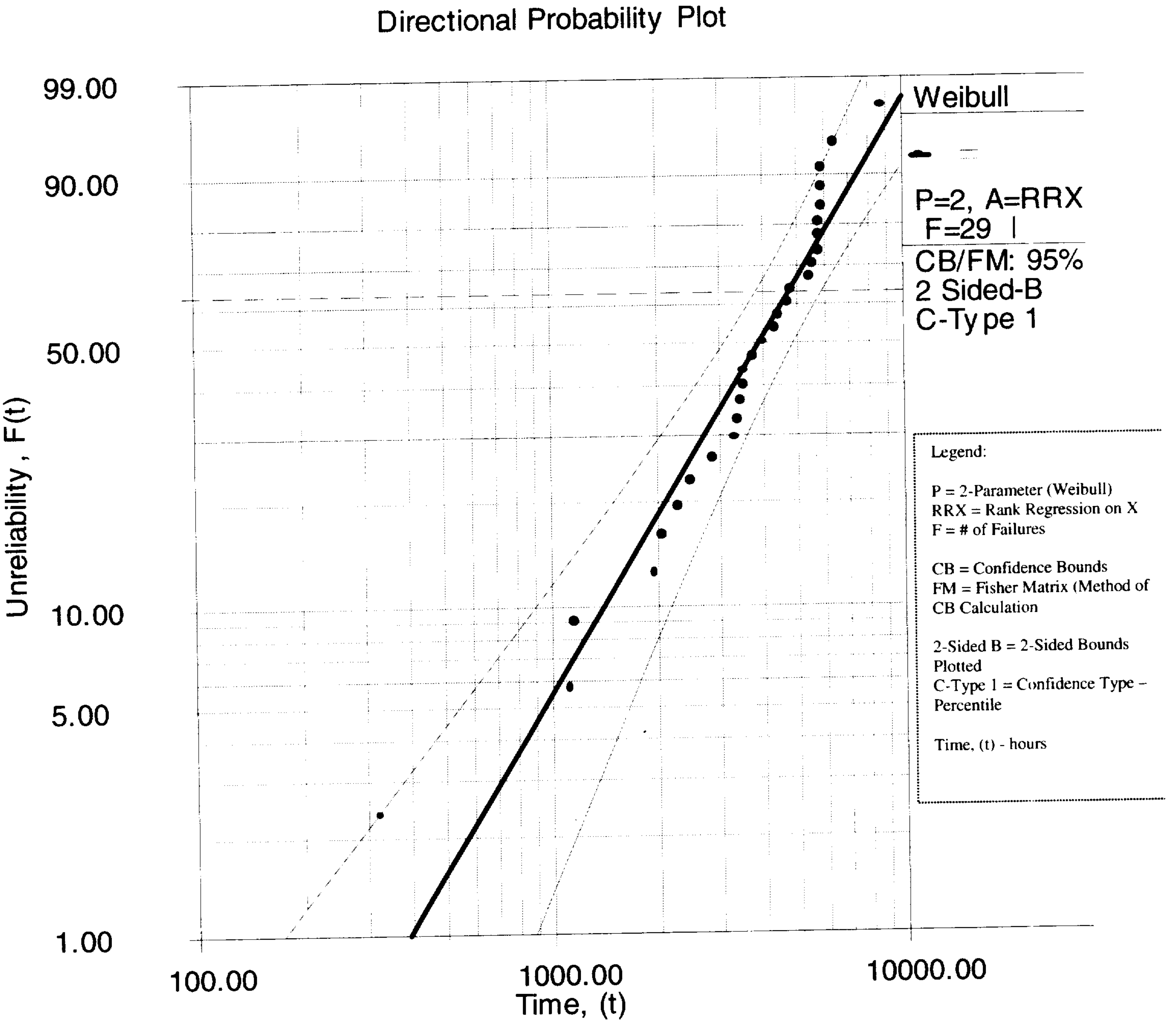
β=2.25, η=5843.58, ρ=0.99



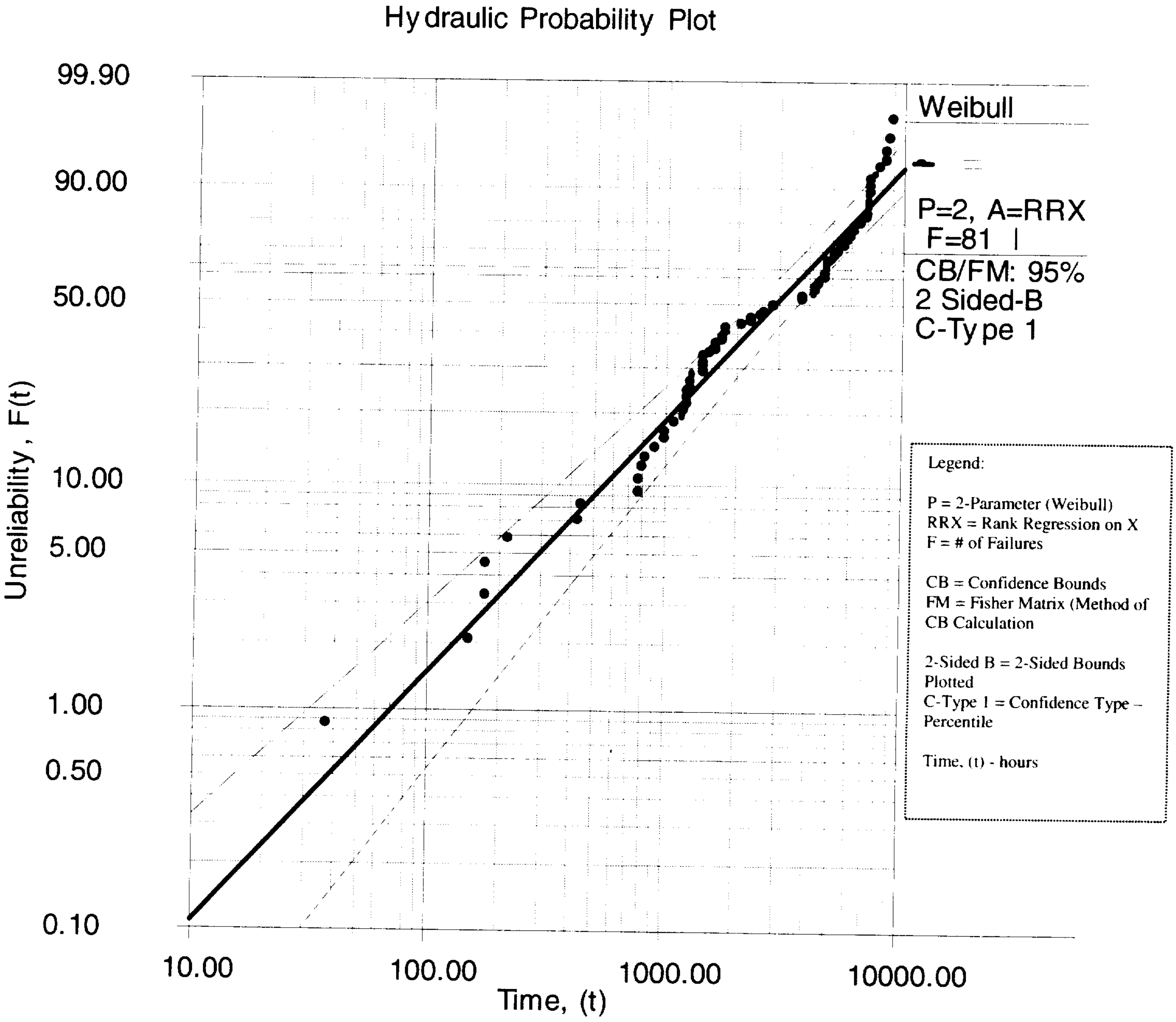
β=0.95, η=3956.09, ρ=0.97



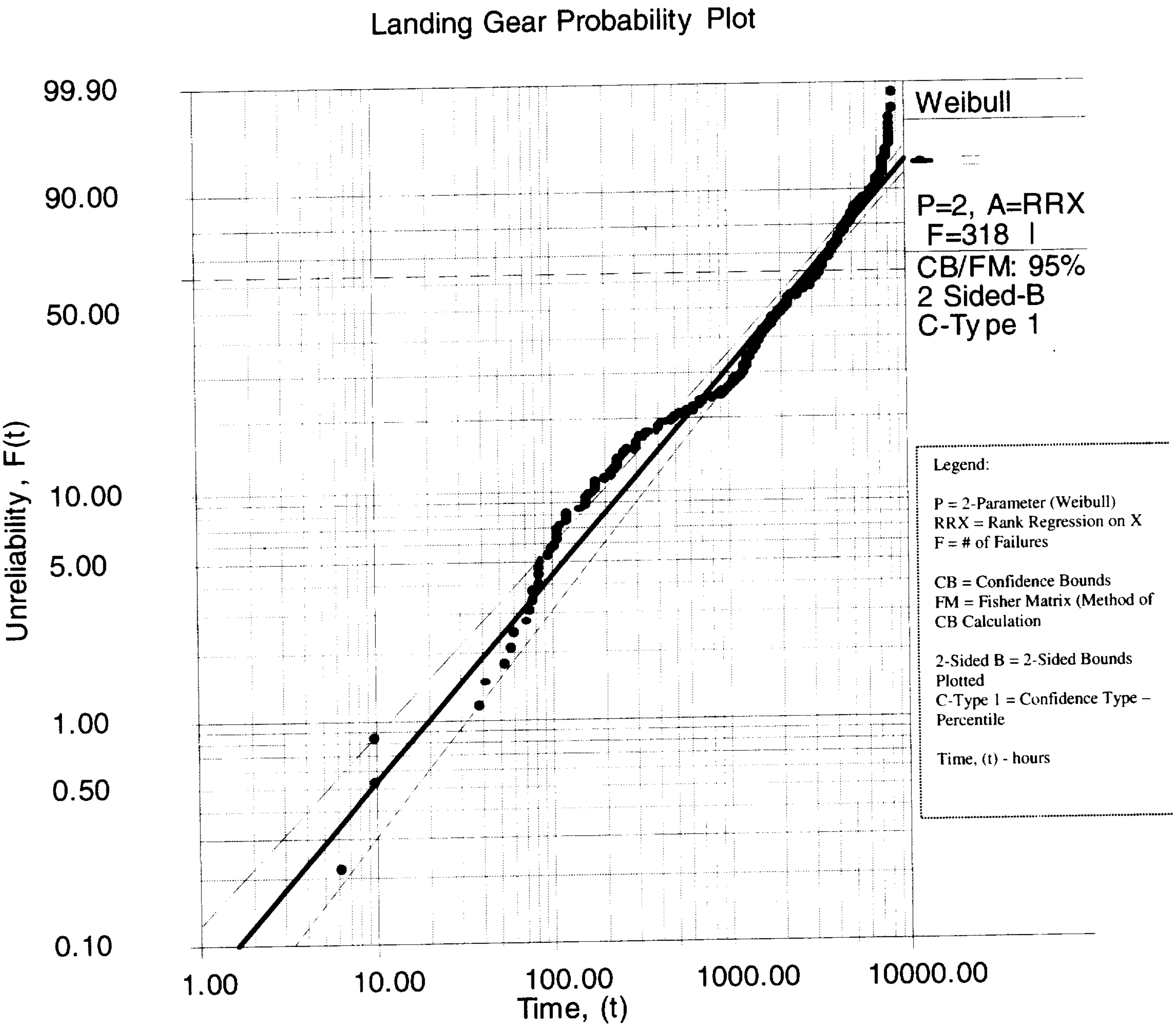
β=0.73, η=2672.10, ρ=0.98



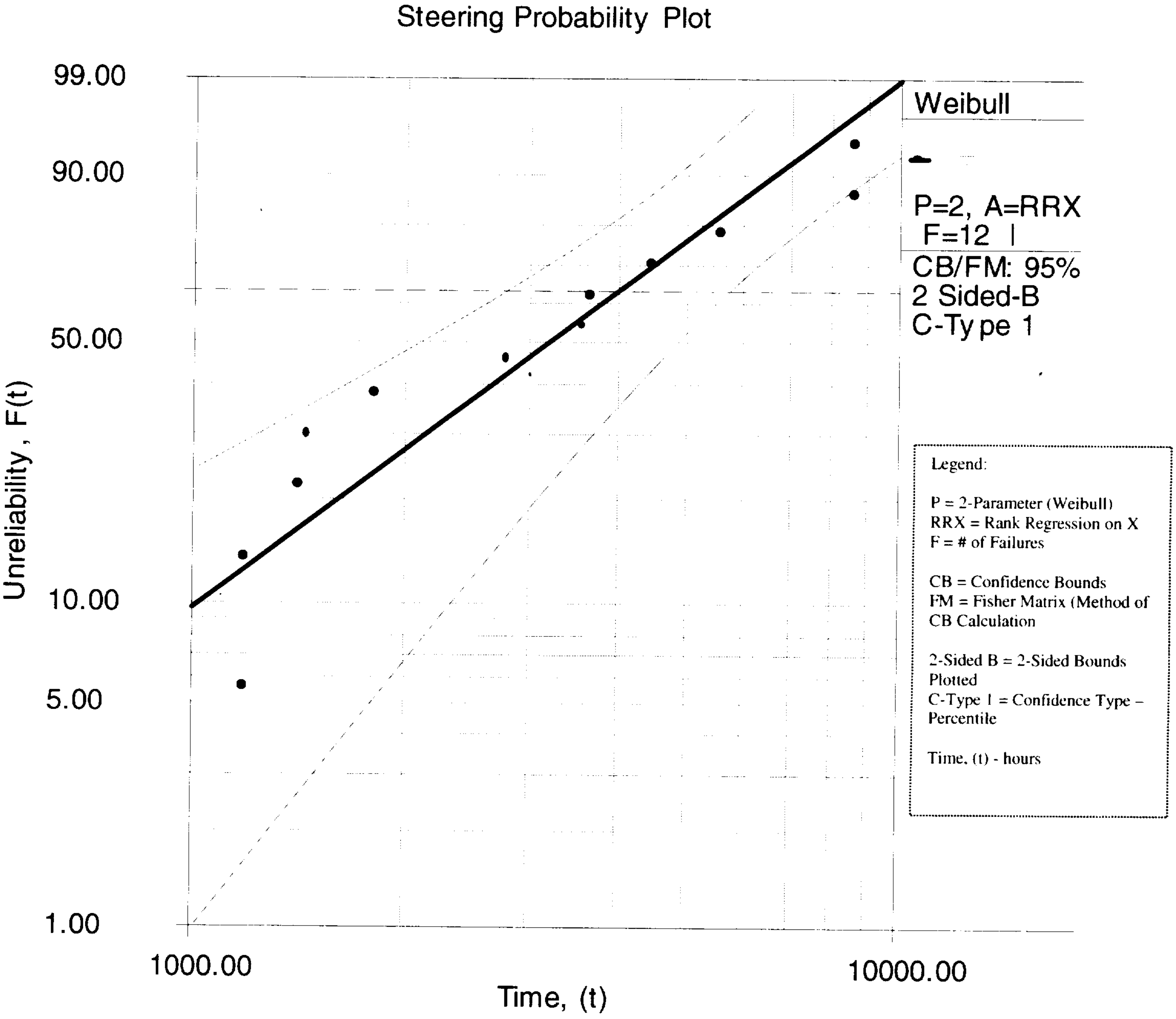
β=1.85, η=4728.93, ρ=0.97



β=1.14, η=3977.39, ρ=0.98


Landing Gear Probability Plot

β=0.92, η=2895.62, ρ=0.99

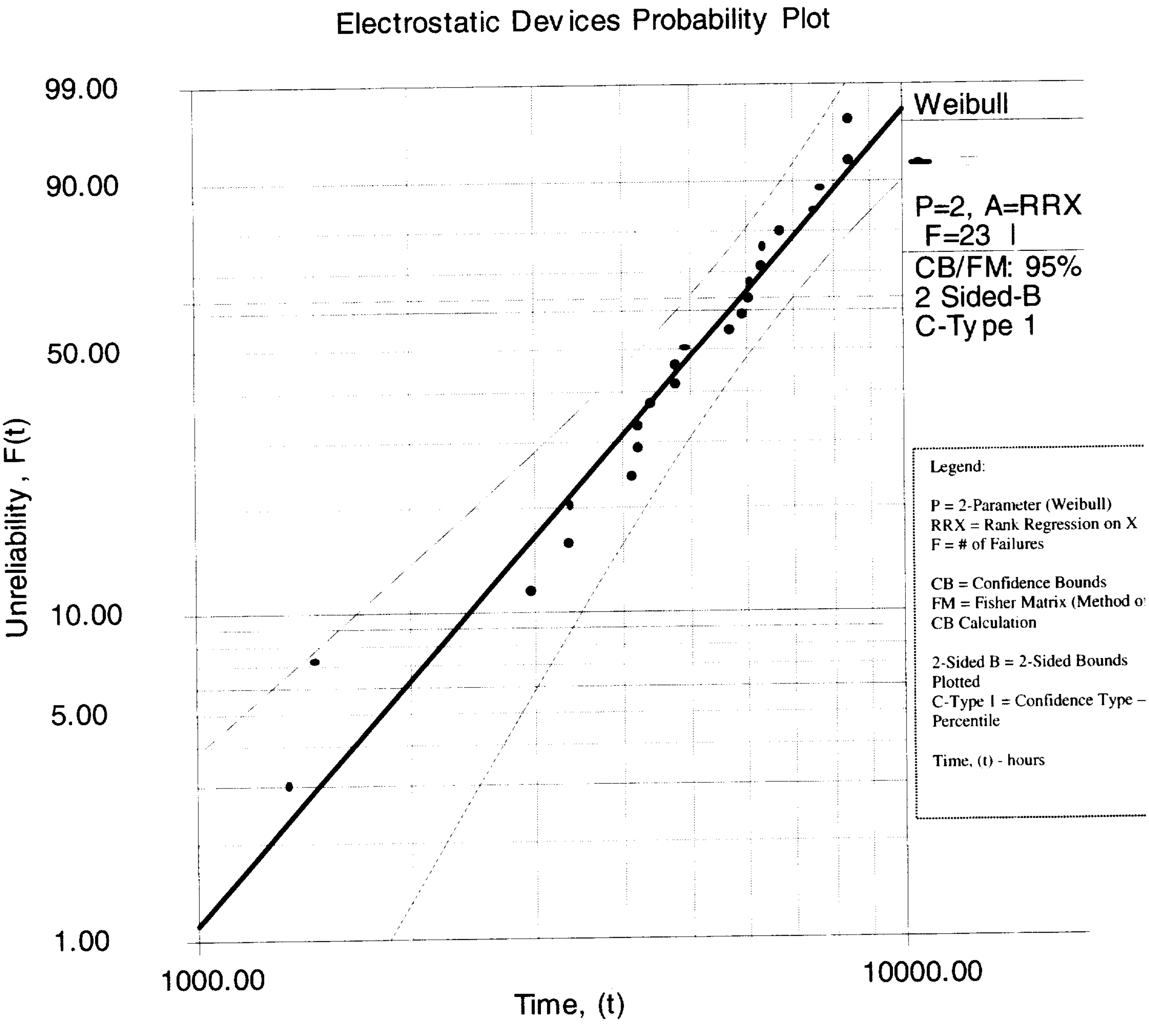


$\beta=1.65$, $\eta=3994.78$, $\rho=0.94$

Appendix D

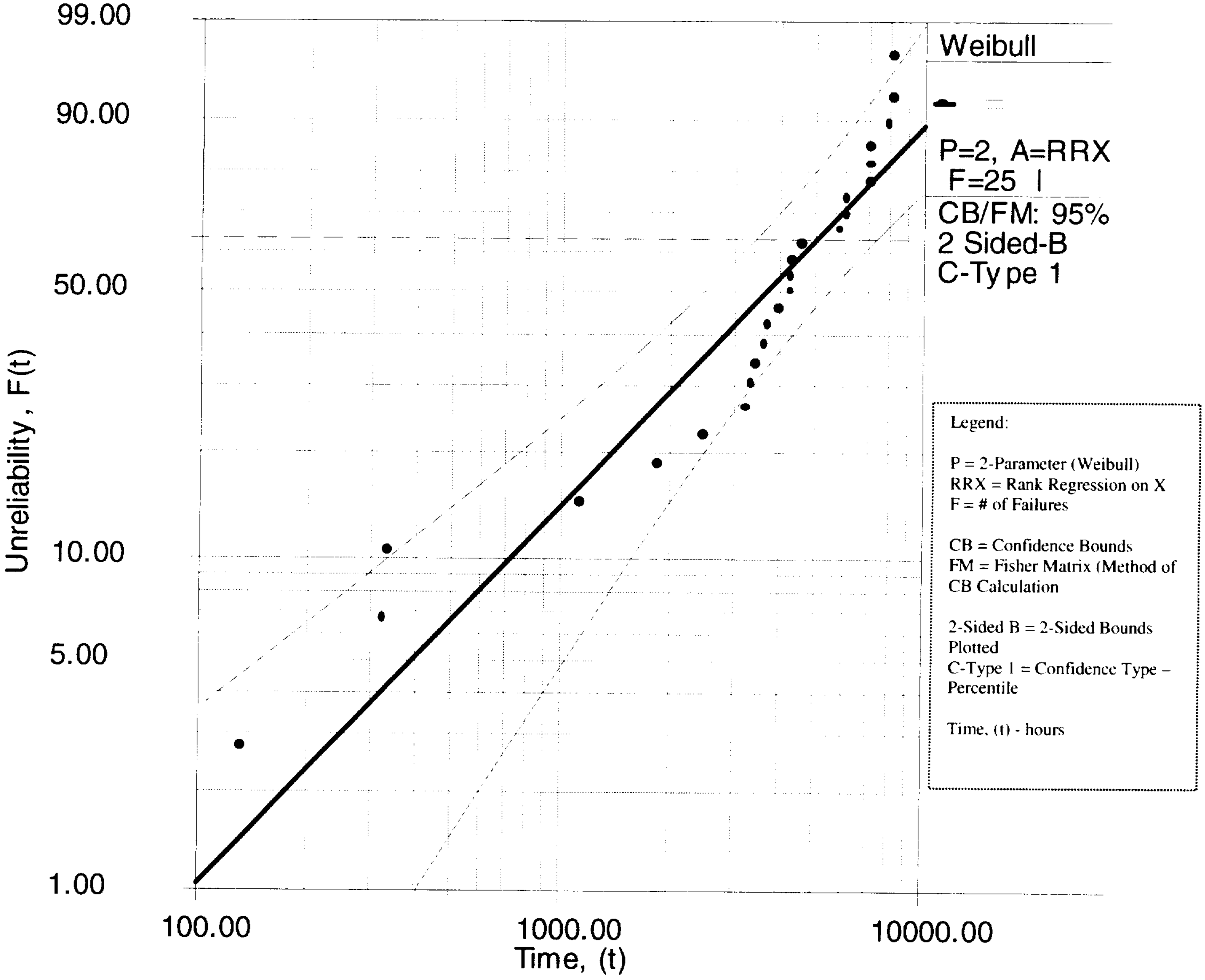
Airframe System

Probability Plots

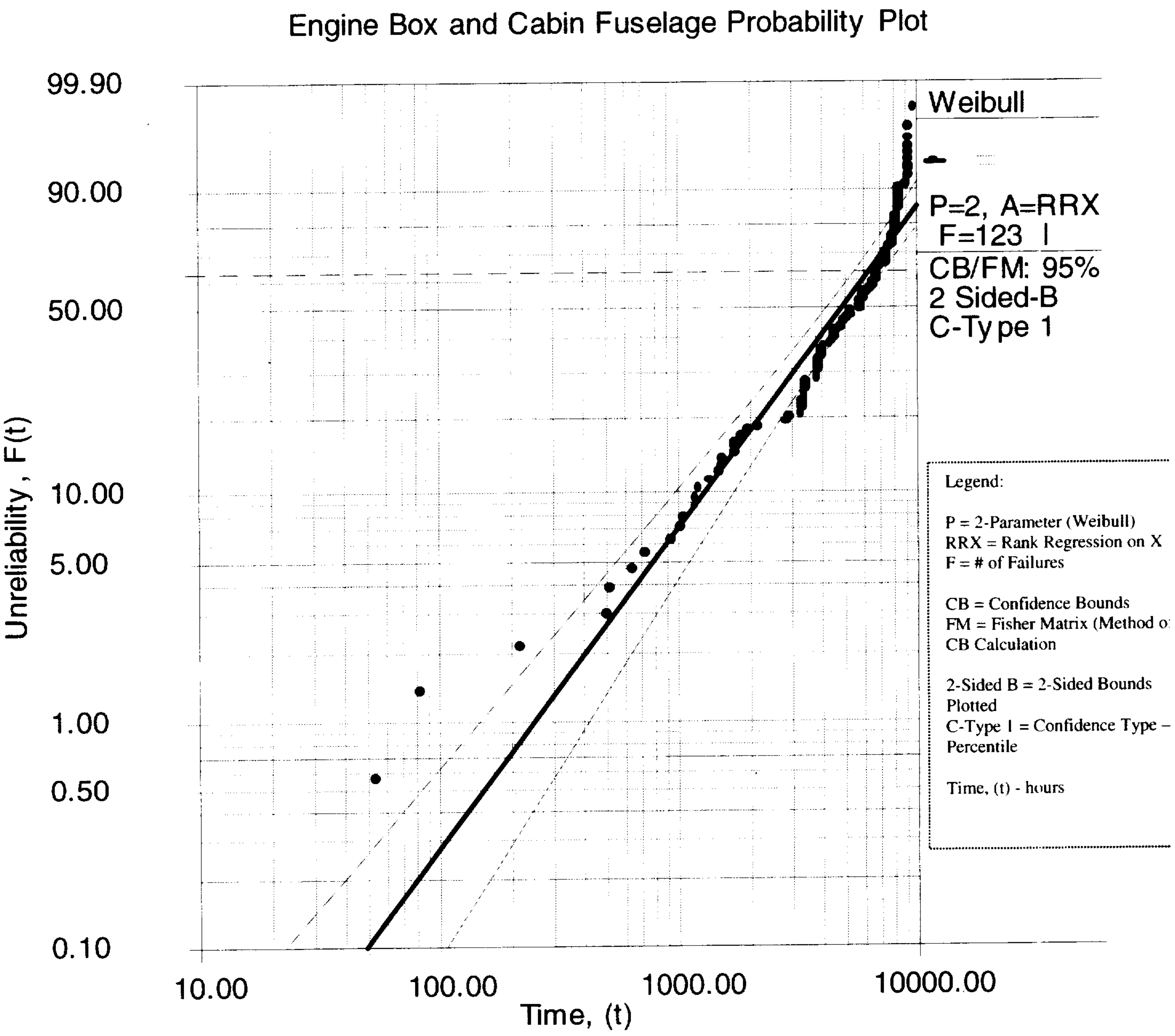


β=2.53, η=5887.53, ρ=0.97

Empennage Probability Plot

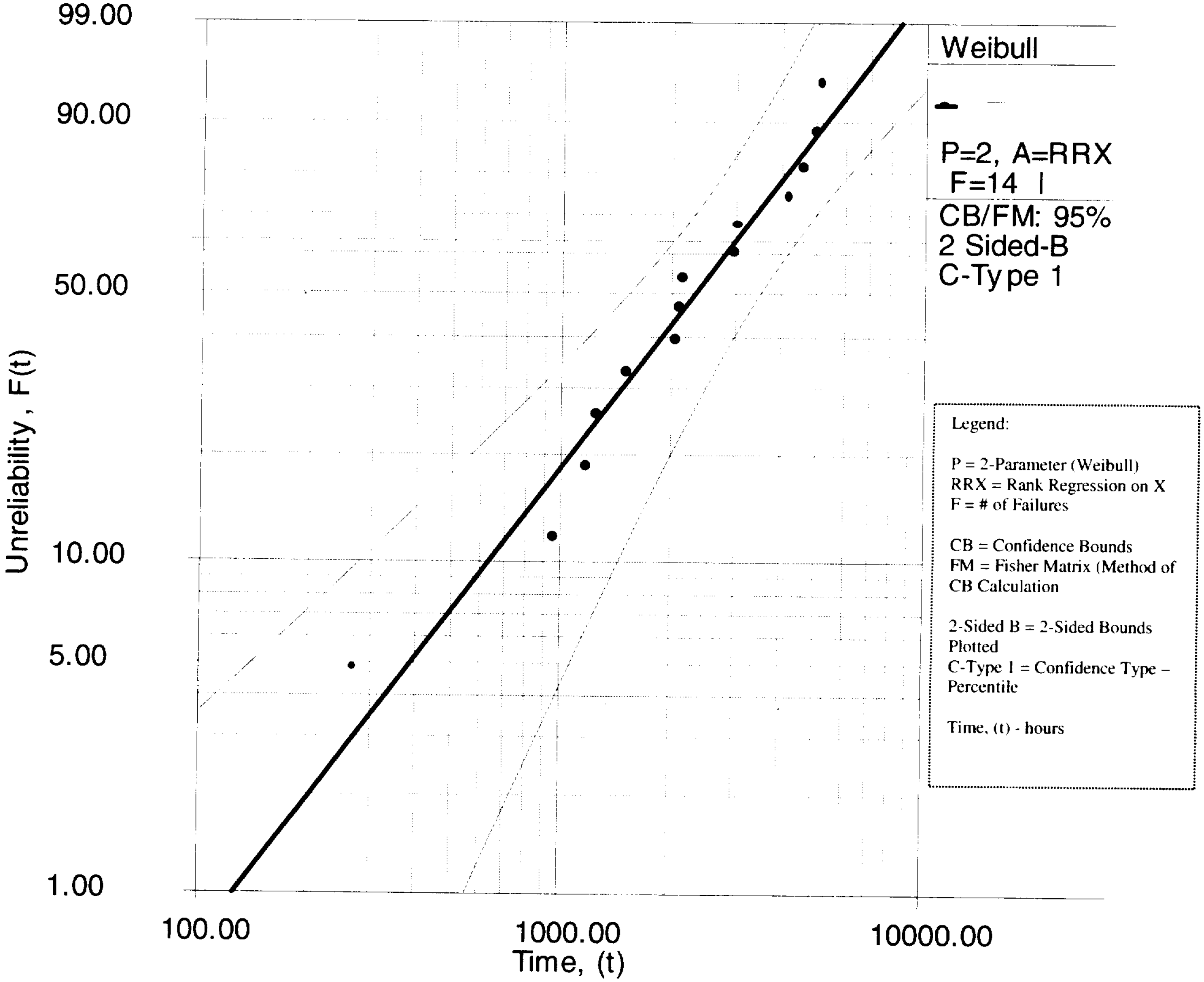


β=1.16, η=5025.35, ρ=0.94

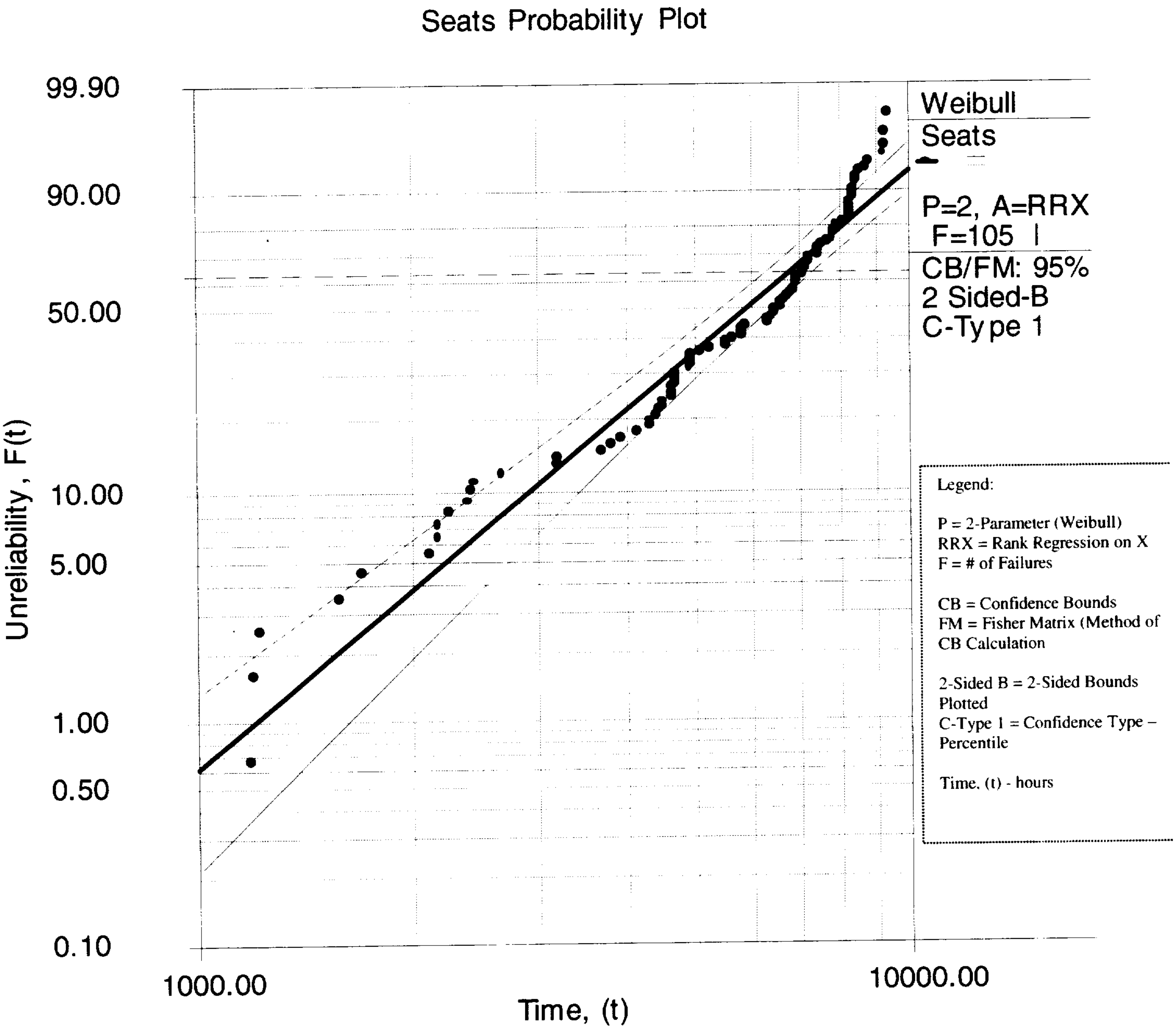


β=1.42, η=6278.95, ρ=0.96

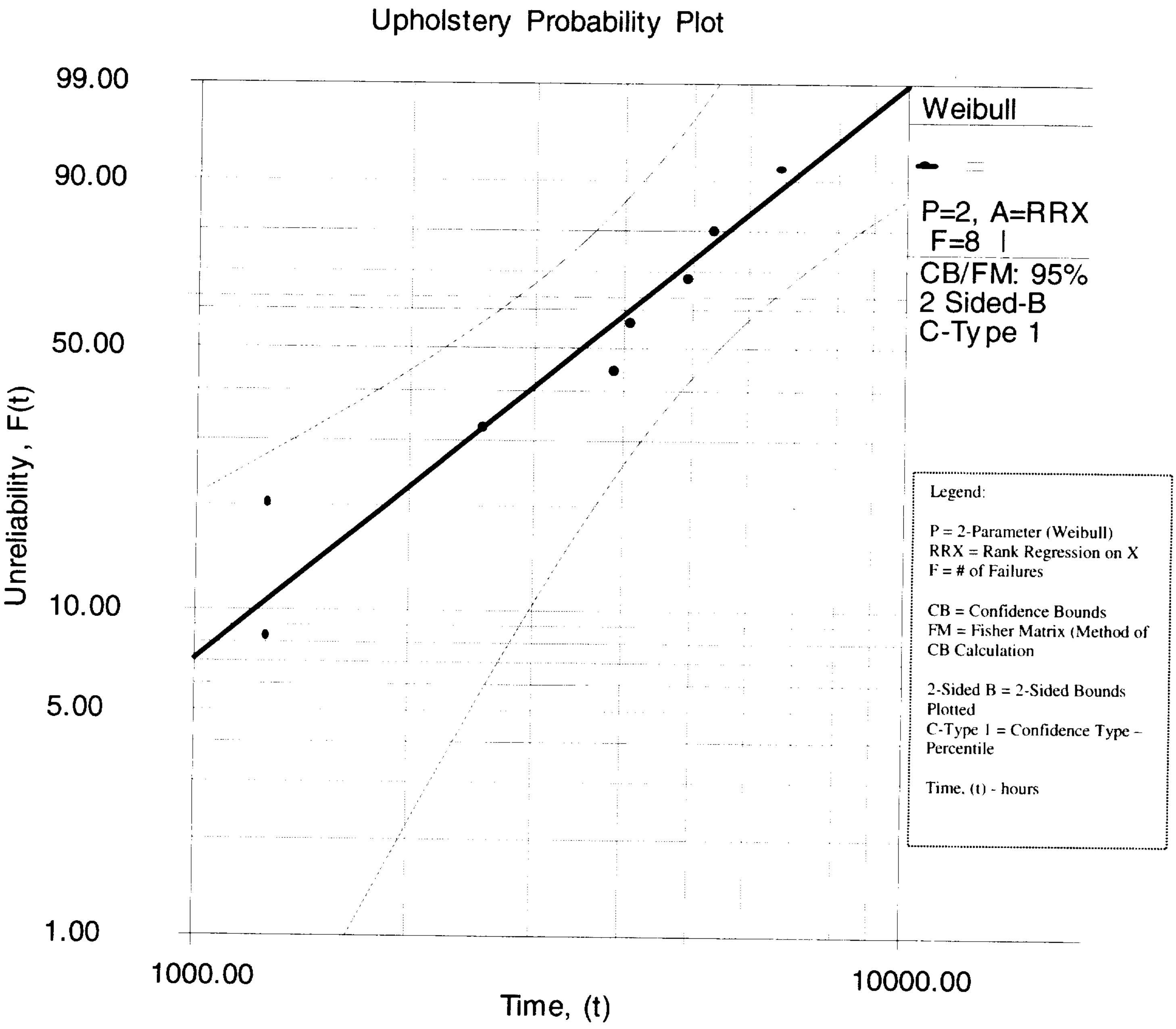
Paint Probability Plot



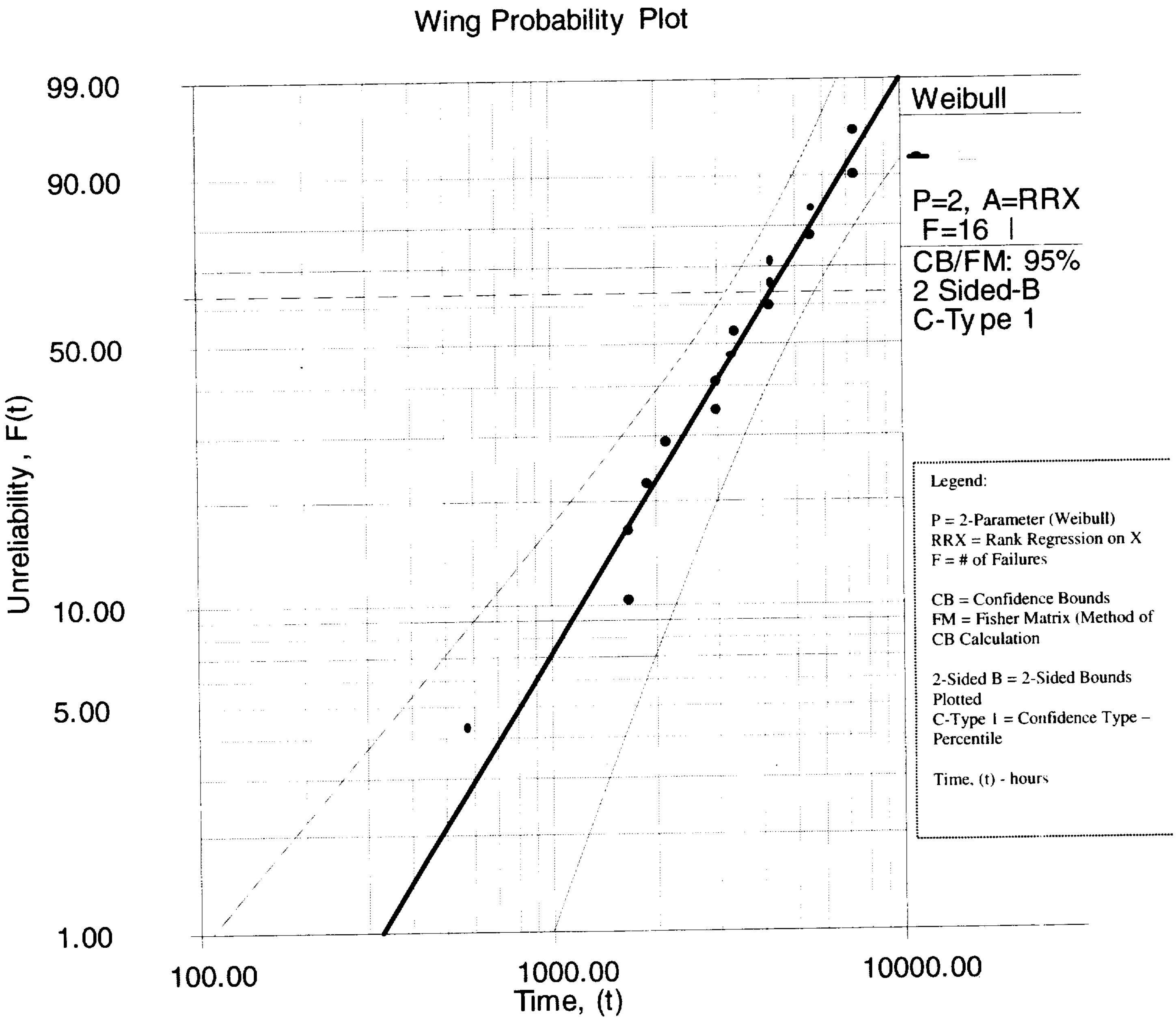
$\beta=1.45$, $\eta=2985.38$, $\rho=0.98$



β=2.66, η=6767.87, ρ=0.98



β=1.79, η=4291.74, ρ=0.96

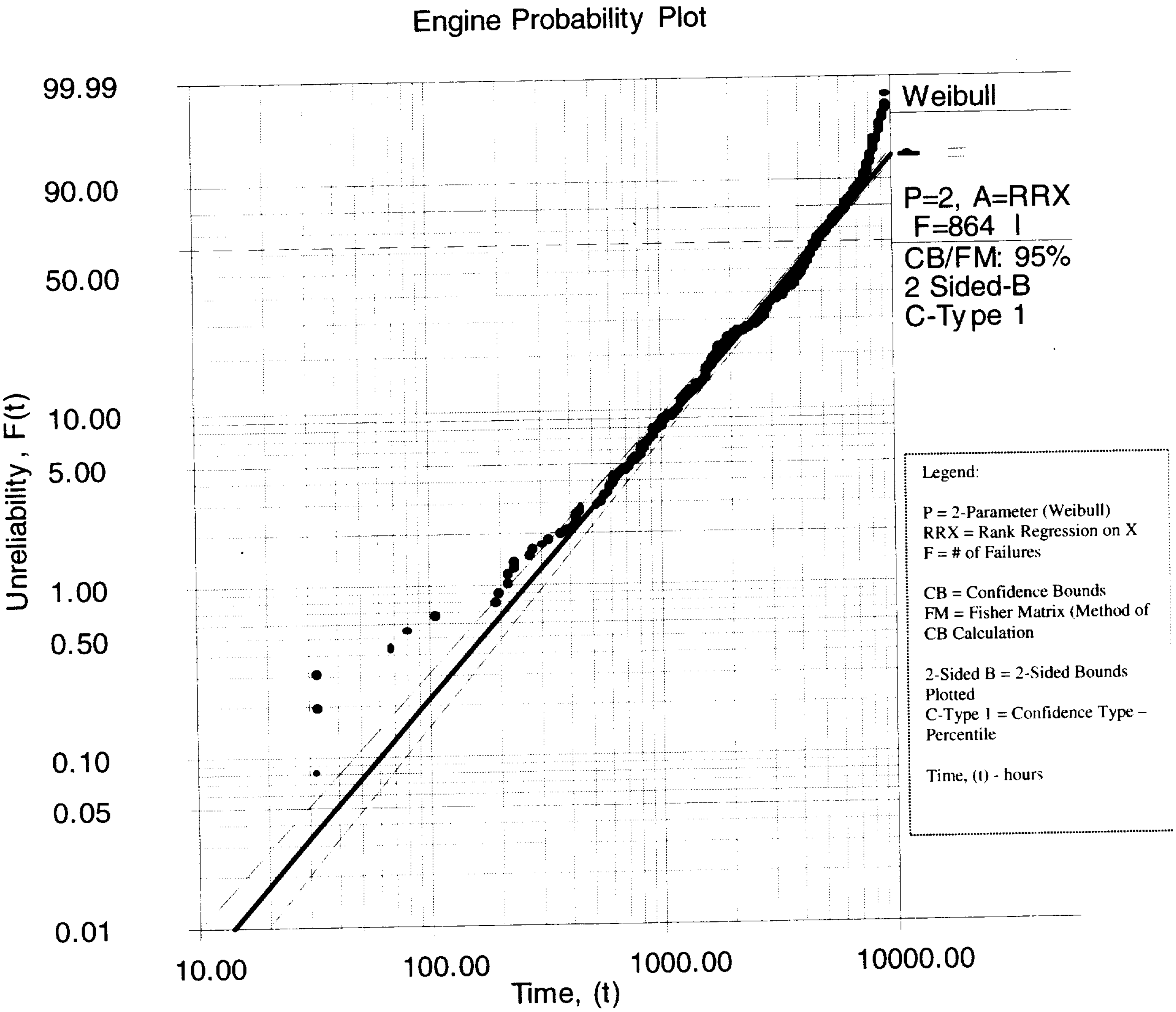


β=1.79, η=4247.38, ρ=0.98

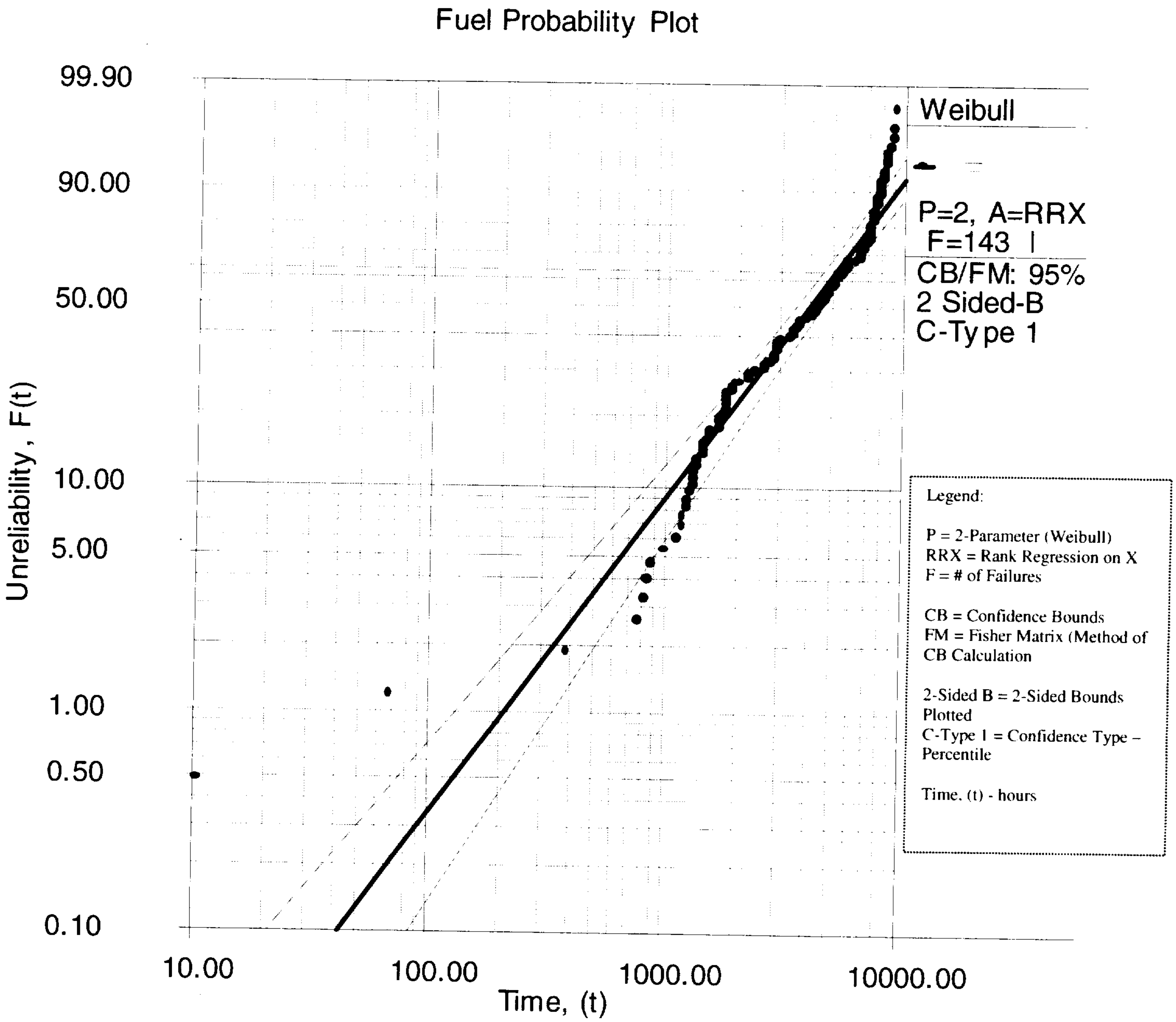
Appendix E

Powerplant System

Probability Plots

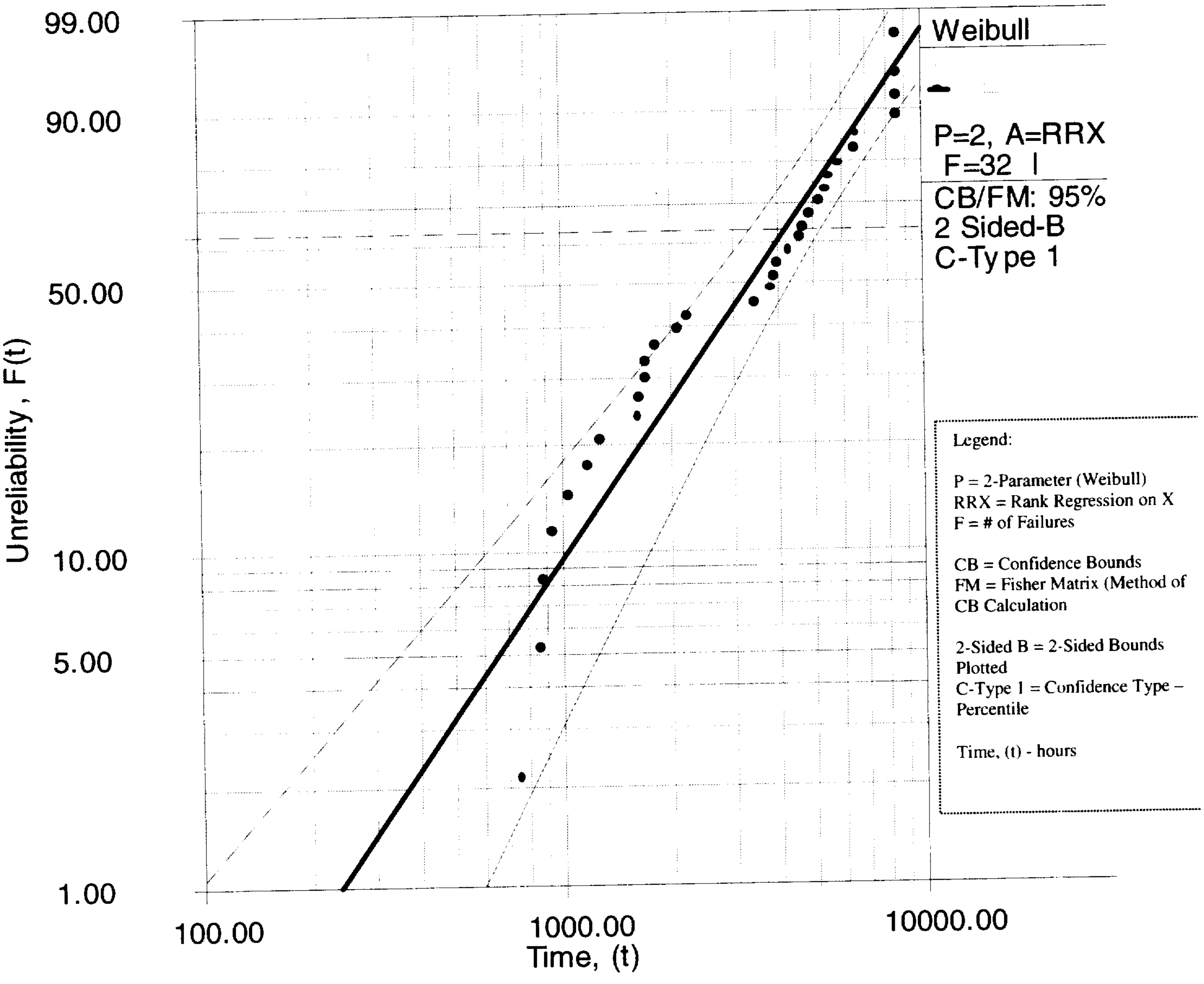


β=1.58, η=4821.49, ρ=0.99



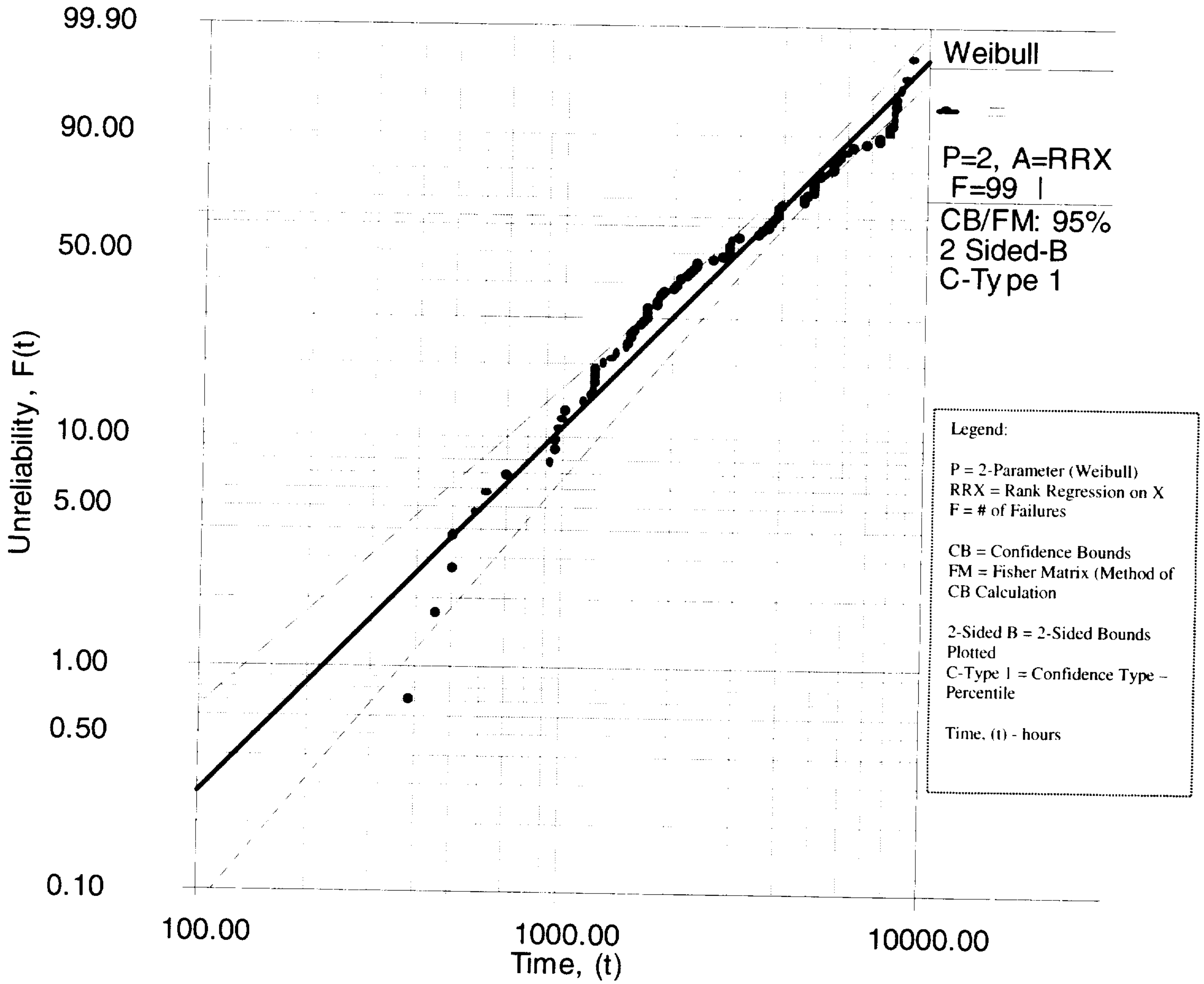
$\beta=1.44$, $\eta=5131.56$, $\rho=0.95$

Heating and Ventilation Probability Plot



$\beta=1.60, \eta=4187.26, \rho=0.96$

Propeller Probability Plot



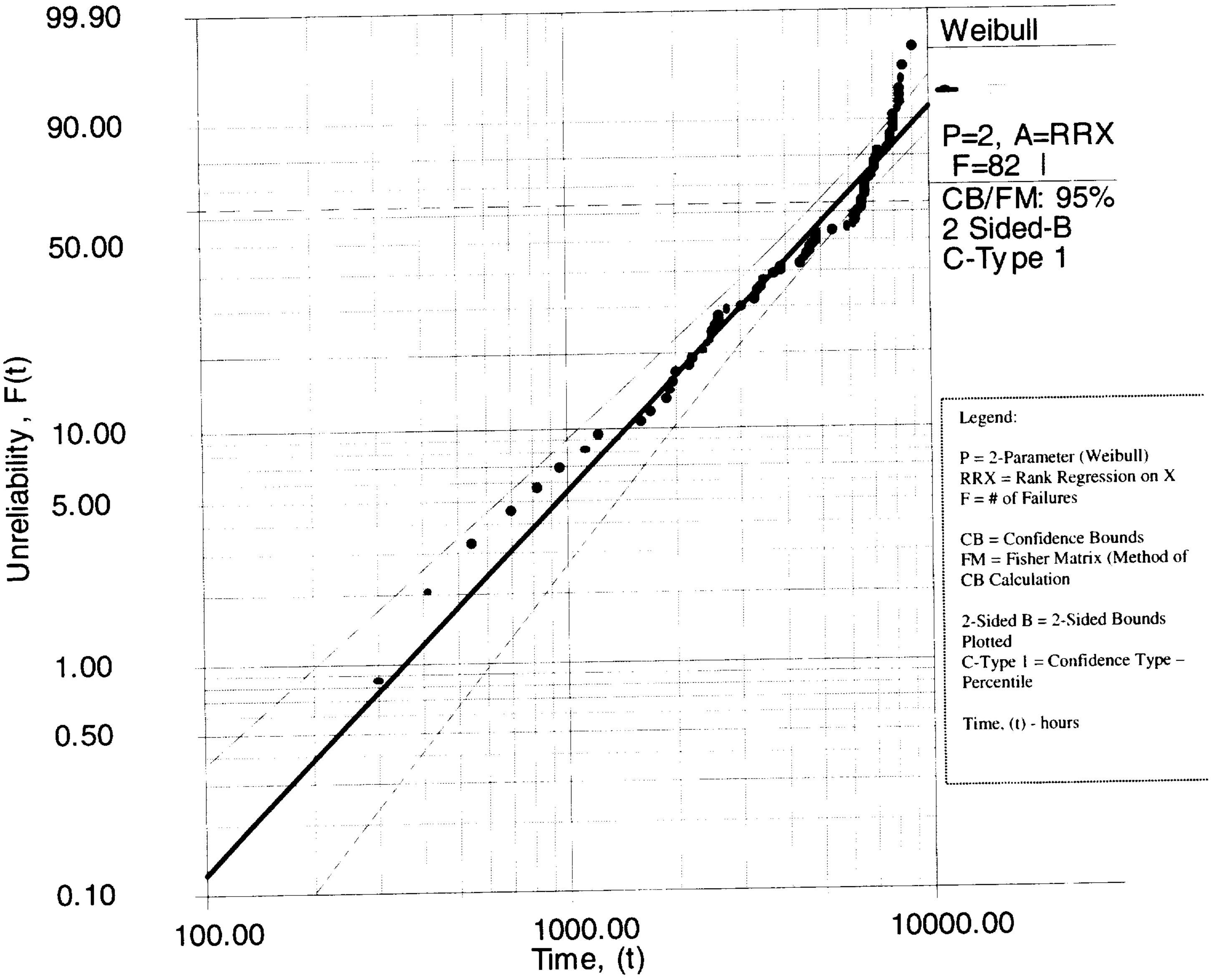
$\beta=1.63$, $\eta=3742.01$, $\rho=0.98$

Appendix F

Electrical System

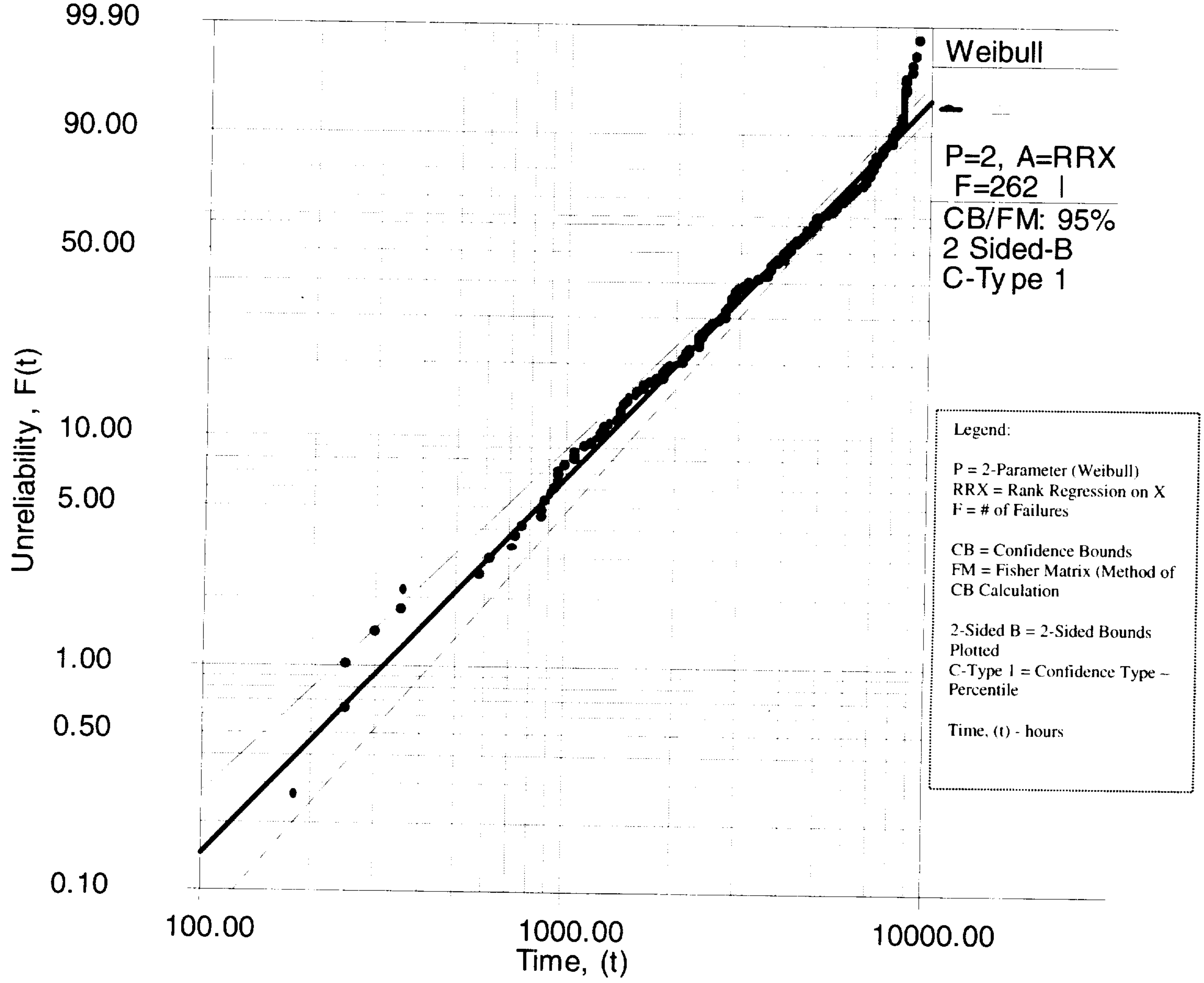
Probability Plots

Lighting Probability Plot



β=1.66, η=5613.87, ρ=0.98

Source and Distribution Probability Plot



$\beta=1.67$, $\eta=4945.24$, $\rho=0.99$

Appendix G

Weibull

Failure Law

The failure rate or hazard rate function is another probability function that is used in reliability. It provides instantaneous (at time t) rate of failure and is defined as follows,

$$h(t) = \frac{f(t)}{R(t)} \qquad \text{Eq. 1}$$

where f(t) = probability density function (PDF) = $-\frac{dR(t)}{dt}$ Eq. 2

and R(t) = reliability function = $\int_0^\infty f(t')dt'$ Eq. 3

For the Weibull distribution,

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^\beta} \qquad \text{Eq. 4}$$

and

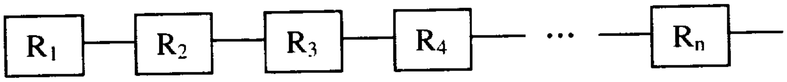
$$f(t) = -\frac{dR(t)}{dt} = \left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1} \bullet e^{-\left(\frac{t}{\alpha}\right)^\beta} \qquad \text{Eq. 5}$$

therefore,

$$h(t) = \frac{\left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1} \bullet e^{-\left(\frac{t}{\alpha}\right)^\beta}}{e^{-\left(\frac{t}{\alpha}\right)^\beta}} = \left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta-1} \qquad \text{Eq. 6}$$

For a system comprised of many components, serial and parallel configurations can be used to describe how they relate to each other. If components are in series, they must each function for the system to function. If they are in parallel, or redundant, configuration, at least one component must function for the system to function.

Using reliability block diagram for components in series,



The reliability of the series system following the exponential failure law is defined as:

$$R_S(t) = \prod_{i=1}^{n} R_i(t) = \prod_{i=1}^{n} e^{-\lambda_i t} = e\sum_{i=1}^{n} -\lambda_i t = e^{-\lambda_s t} \qquad \text{Eq. 7}$$

Where, by using Equation 1, the constant failure rate model can be derived,

$$h_s(t) = \frac{\left(-e^{-\sum_{i=1}^{n}\lambda_i t}\right)\bullet\left(-\sum_{i=1}^{n}\lambda_i t\right)}{\left(e^{-\sum_{i=1}^{n}\lambda_i t}\right)} = \lambda_s = \sum_{i=1}^{n}\lambda_i \qquad \text{Eq. 8}$$

For components governed by the Weibull failure law, the reliability of a system comprised of components in series is,

$$R_S(t) = \prod_{i=1}^{n} R_i(t) = \prod_{i=1}^{n} e^{-\left(\frac{t}{\alpha_i}\right)^{\beta_i}} = e^{-\sum_{i=1}^{n}\left(\frac{t}{\alpha_i}\right)^{\beta_i}} \qquad \text{Eq. 9}$$

and from Equation 1 above, the system hazard rate function as governed by the Weibull failure law is,.

$$h_s(t) = \frac{e^{-\sum_{i=1}^{n}\left(\frac{t}{\alpha_i}\right)^{\beta_i}}\bullet\sum_{i=1}^{n}\left(\frac{\beta_i}{\alpha_i}\right)\left(\frac{t}{\alpha_i}\right)^{\beta_i-1}}{e^{-\sum_{i=1}^{n}\left(\frac{t}{\alpha_i}\right)^{\beta_i}}} = \sum_{i=1}^{n}\left(\frac{\beta_i}{\alpha_i}\right)\left(\frac{t}{\alpha_i}\right)^{\beta_i-1} \qquad \text{Eq. 10}$$

Appendix H

Weibull Parameter Bounds

System	Subsystem	Lower Beta	Beta	Upper Beta	Lower Alpha	Alpha	Upper Alpha	Lower Lambda	Lambda	Upper Lambda	Lower System Lambda	System Lambda	Upper System Lambda
Electrical	Lighting	1.38	1.66	2.01	4881.12	5613.87	6456.61	2.21E-05	3.15E-06	2.76E-07	**3.30E-05**	**6.82E-06**	**1.28E-06**
	Source and Distribution	1.51	1.67	1.86	4581.00	4945.24	5338.43	1.09E-05	3.67E-06	1.01E-06			
Airframe	Electrostatic Devices	1.80	2.53	3.57	4953.63	5887.53	6997.51	1.73E-06	1.12E-08	6.65E-12	**1.96E-03**	**1.23E-04**	**4.28E-06**
	Engine Box and Cabin Fuselage	1.21	1.42	1.67	5459.94	6278.95	7220.83	5.16E-05	1.20E-05	2.03E-06			
	Empennage	0.82	1.16	1.66	3425.02	5025.35	7373.44	7.67E-04	7.75E-05	2.11E-06			
	Paint	0.94	1.45	2.25	2021.67	2985.38	4408.48	6.59E-04	2.89E-05	1.32E-07			
	Seats	2.25	2.66	3.14	6266.92	6767.87	7308.88	5.98E-08	3.38E-09	1.06E-10			
	Upholstery	0.99	1.79	3.23	2827.89	4291.74	6513.35	3.72E-04	2.34E-06	8.35E-11			
	Wing	1.21	1.79	2.67	3174.16	4247.38	5683.47	1.04E-04	2.30E-06	5.05E-09			
Power plant	Engine	1.49	1.58	1.67	4607.24	4821.49	5045.71	1.25E-05	6.92E-06	3.69E-06	**1.93E-04**	**3.63E-05**	**8.28E-06**
	Fuel	1.25	1.44	1.66	4534.24	5131.56	5807.56	5.19E-05	1.44E-05	3.15E-06			
	Heating and Ventilation	1.21	1.60	2.12	3339.30	4187.26	5250.54	9.43E-05	7.37E-06	2.07E-07			
	Propeller	1.40	1.63	1.90	3294.36	3742.01	4250.49	3.46E-05	7.61E-06	1.23E-06			
Control													
FCS	Trim	0.58	0.73	0.93	1769.71	2672.10	4034.62	3.61E-03	1.41E-03	3.67E-04	**5.09E-03**	**2.01E-03**	**4.13E-04**
	Longitudinal	1.17	1.57	2.10	3719.30	4718.22	5985.43	1.05E-04	7.48E-06	1.72E-07			
	Lateral	1.72	2.25	2.95	5005.23	5843.58	6822.36	2.74E-06	7.00E-08	4.74E-10			
	Flap	0.74	0.95	1.23	2804.80	3956.09	5579.97	1.33E-03	3.30E-04	4.57E-05			
	Directional	1.35	1.85	2.52	3810.81	4728.93	5868.24	3.66E-05	1.39E-06	1.23E-08			
	Autopilot	2.63E-04											
GCS	LG	0.84	0.92	1.01	2547.80	2895.62	3290.92	8.66E-04	5.16E-04	2.86E-04	**1.51E-03**	**6.37E-04**	**3.10E-04**
	Steering	1.07	1.65	2.54	2780.18	3994.78	5740.02	2.46E-04	5.96E-06	1.12E-08			
	Hydraulic	0.95	1.14	1.37	3241.74	3977.39	4879.98	4.03E-04	1.16E-04	2.37E-05			

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This reliability study estimates Complex General Aviation (GA) Aircraft System reliability. As part of an effort to successfully improve the safety and reliability of the next generation of GA aircraft, a benchmarking of the current reliability of GA Aircraft Systems was performed. Specifically, Complex GA Aircraft System reliability was estimated using data obtained from the logbooks of a random sample of the Complex GA Aircraft population. The results of this analysis provide insight into the current reliability of Complex GA Aircraft Systems (i.e., Airframe, Electrical, Powerplant, Flight Control and Ground Control Systems). In addition, an estimate of Cockpit Instrumentation reliability, performed in an earlier report, is also presented.

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